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Reverse Osmosis Treatment to Remove Inorganic Contaminants from Drinking Water

Charlotte Harbor Water Association, Inc.
Harbour Heights, FL

Prepared for

Environmental Protection Agency, Cincinnati, OH

Dec 87

removals were expected by all RO membranes. The test data confirmed the expectations: the results from four membrane tests showed excellent removals of greater than 98 percent. The conclusion is, therefore, that uranium is extremely well removed by RO treatment.

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REVERSE OSMOSIS TREATMENT TO REMOVE INORGANIC CONTAMINANTS FROM DRINKING WATER

by

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Cooperative Agreement
No. CR-807358

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OFFICE OF RESEARCH AND DEVELOPMENT
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16. ABSTRACT

The purpose of this research project was to determine the removal of inorganic contaminants from drinking water using several 'state-of-the-art' reverse osmosis membrane elements. A small 5 KGPD reverse osmosis system was utilized and five different membrane elements were studied individually with the specific inorganic contaminants added to several natural Florida ground waters. Testing of each contaminant was conducted for a period of 1 - 13 days during which both operational and chemical data were collected.

This report presents the results of the tests for the removal capabilities of various reverse osmosis membrane elements for the following inorganic contaminants: fluoride, cadmium, mercury, chromium (III and VI), arsenic (III and IV), selenium (IV and VI), nitrate, nitrite, lead, uranium, radium, molybdenum and copper. Removal data were also collected on naturally occurring susbtances, i.e. total hardness, chlorides, total dissolved solids and in some cases sodium and calcium.

The fine reverse osmosis membrane elements selected for the study were: (1) Toray SC 3100, (2) Filmtec BW30-4021, (3) Dow low pressure 5K, (4) Dupont B-9 Model 0440-042, and (5) Hydranautics P/N 4040 LSY-1FCl.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and prevent it's deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water and land from manufacturing processes and subsequent uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report presents information on the application of several reverse osmosis membrane elements to remove inorganic contaminants from drinking water. The data presented are helpful in solving small community problems in meeting the inorganic drinking water regulations.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

The purpose of this research project was to determine the removal of inorganic contaminants from drinking water using several 'state-of-the-art' reverse osmosis membrane elements. A small 3785 L/d (1000 gpd) reverse osmosis system was utilized and five different membrane elements were studied individually with the specific inorganic contaminants added to several natural Florida ground waters. Testing of each contaminant was conducted for a period of 1 - 13 days during which both operational and chemical data were collected.

This report presents the results of the tests for the removal capabilities of various reverse osmosis membrane elements for the following inorganic contaminants: fluoride, cadmium, mercury, chromium (III and VI), arsenic (III and V), selenium (IV and VI), nitrate, nitrite, lead, uranium, radium, molybdenum and copper. Removal data were also collected on naturally occurring substances, i.e. total hardness, chlorides, total dissolved solids and in some cases sodium and calcium.

Reverse osmosis membrane elements selected for the study were as follows:

1. Toray SC 3100
2. Filmtec BW30-4021
3. Dow low pressure 5K
4. Dupont B-9 Model 0440-042
5. Hydranautics P/N 4040 LSY-IFCl

This report was submitted in fulfillment of Cooperative Agreement CR-807358 by the Charlotte Harbor Water Association, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period March 1980 to March 1985 and the work was completed as of April 1985.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

WERL - Water Engineering Research Laboratory
CHWA - Charlotte Harbor Water Association, Inc.
DWRD - Drinking Water Research Division, USEPA
EMSL - Environmental Monitoring & Support Laboratory, USEPA
EPA - Environmental Protection Agency
EQL - Environmental Quality Laboratory
gpd - Gallons per day
Kgpd - Thousand gallons per day
gpm - Gallons per minute
L/s - Liters per second
m(3) - Cubic meters
mg/L - Milligrams per liter
NIPDWR - National Interim Primary Drinking Water Regulations
pCi/L - Picocuries per liter
psig - Pounds per square inch gage
kPa - Kilopascals
RO - Reverse Osmosis
TDS - Total dissolved solids
TH - Total hardness

Symbols

F - Fluoride
Cd - Cadmium
Hg - Mercury
Cr - Chromium
As - Arsenic
Se - Selenium
NO_3 - Nitrate
$NO_3(N)$ - Nitrate nitrogen
Pb - Lead
U - Uranium
Ra - Radium
Mo - Molybdenum
Cu - Copper
NO_2 - Nitrite
$NO_2(N)$ - Nitrite nitrogen

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Special acknowledgement is given to Mr. Ben Mohlenhoff, Mr. Stu McLellan, Mr. Chip Harris and Mr. William K. Hendershaw of Basic Technologies, Inc. for providing engineering support as well as contributing both time and effort with regard to presentation of specifications of available state-of-the-art membrane elements. Mr. Ben Mohlenhoff and Mr. Chip Harris also contributed their time and efforts to technical problems associated with the servicing of the RO test system.

The help of Herb Braxton, Mark Guttadauro, and Jim Tenhundfeld, USEPA, in the processing and tabulation of all the data is also acknowledged.

SECTION 1

INTRODUCTION

Reverse osmosis (RO) is a relatively new water treatment process; it has been applied successfully for desalting brackish water for domestic use for less than two decades. RO systems typically operate at 5520 kPa (800 psig) for sea water applications [35,000 mg/L Total Dissolved Solids (TDS)] and at 2760 kPa (400 psig) for brackish water applications with TDS ranging from 1,000 to 15,000 mg/L.

During the late 1970'S, progress was made in membrane technology wherein advancements not only occurred with the traditional 2760 kPa (400 psig), 90 percent TDS rejecting membranes, but even more significantly with the reduced pressure membranes that require approximately 1880 kPa (200 psig) to achieve high TDS rejection in excess of 90 percent. These membranes also operate in a wider range of feed water pH and thus are capable of increasing applications. The major advantage, however, is the greatly reduced energy requirements and therefore significantly lower operating costs.

RO is effective for the removal of most dissolved solids; specific removal in most cases is dependent upon the weight, size, and valence of the ionic specie. Extensive studies have been conducted to ascertain the efficacy of RO to reject the common water constituents such as sodium, chloride, sulfate, TDS, calcium, etc., however, very limited experimentation has been performed to evaluate the effectiveness of RO to remove from drinking water many of the heavy metals and other inorganic contaminants listed in the National Interim Primary Drinking Water Regulations (NIPDWR) (1). The investigations have generally consisted of laboratory studies and most results have not been verified on either a pilot plant or full scale level (2-5).

The objective of this research project was to determine the rejection of the inorganic contaminants listed in the NIPDWR using several state-of-the-art RO membrane elements. Limited tests were also conducted with several contaminants also being considered for regulation in the future. Because of various problems associated with the specific chemistry of the raw water, some of the contaminants were not investigated. This project was a continuation of a similar project that was reported by Huxstep (6).

This final report describes the RO test system and components, experimental procedures, and results of tests with fluoride, nitrate, arsenic (III & V), selenium (IV & VI), chromium (III & VI), cadmium, mercury, lead, uranium, radium, molybdenum, copper and nitrite.

SECTION 2

CONCLUSIONS

The primary objective of this study was the development of reverse osmosis treatment data on drinking water contaminants regulated by the USEPA using several state-of-the-art RO membranes. Using spiked Florida ground waters, five RO membranes were used in the study with individual tests lasting from one to 13 days. Operating conditions for each membrane varied according to the manufacturer's operating specifications. Although the five RO membranes were operated under different conditions (pressure, recovery rate), rejections of the natural substances measured in the test waters and the spiked contaminants were generally in agreement for all membranes.

Considering the test data from all four membranes as a whole, the contaminants (natural and spiked) can be grouped according to removal capability as follows:

Highly removed (above 95 percent) - As+5, Ca, Cd, Cr+3, Cr+6, Cu, Pb, Mo, Na, Ra, Se+4, Se+6, U, hardness, TDS

Moderately removed (85 - 94 percent) - F, Cl^-, NO_3, NO_2

Poorly removed (below 85 percent) - As+3, Hg(I)

Wide variation in removals occur with four contaminants: As+3, Hg, F, and NO_3. Because nitrite tests were limited to a two day test with one membrane, no general conclusion on variability for nitrite removal can be made. The variation in removals of these contaminants occurred among membranes and within each membrane test. The reason for the variation is concluded to be the chemistry of the contaminants and water matrix, membrane material, and test conditions. In the case of mercury, analytical procedures may also have contributed to the variation in results.

SECTION 3

REVERSE OSMOSIS PILOT PLANT SYSTEM

SYSTEM COMPONENTS

The reverse osmosis pilot plant system was housed in the Charlotte Harbor Water Association, Inc. (CHWA) water treatment plant facilities located in Harbour Heights, Florida. The system consisted of a 19 m^3/d (5 kgpd) reverse osmosis module with a high pressure pump, a 378.5 L (100 gal) stainless steel tank with a low pressure pump which acted as a feedwater source, pretreatment in the form of 5 micrometer filtering, a cooling unit for temperature stabilization, and a disposal line through which spent water was directed to a disposal pond. The RO module and feed water tank occupied an area of approximately 5.4 m^2 (58 sq ft).

After extensive consideration of the primary intent of this project, the system was altered from a standard flow configuration with no recirculation to a continuous recirculation mode of operation by returning both permeate and concentrate to the feedwater holding tank. Because considerable heat was generated by this system design, a heat exchange unit was installed. This system, shown in Figure 1, is similar to that defined by the ASTM "Standard Test Method for Operating Characteristics of Reverse Osmosis Devices." (7)

The RO test system was obtained from a previous U.S. EPA research project and refurbished by Basic Technologies, Inc., Riviera Beach, Florida.

Reverse Osmosis Test Unit

The RO test system was a 19 m^3 (5kgpd) high pressure 2760 kPa (400 psig) unit with a single fiberglass reinforced plastic pressure vessel into which a single 4 inch membrane element could be loaded. Three of the membrane elements tested were provided by the manufacturer already contained within a pressure vessel ready for operation. The actual permeate capacity of this system was dependent upon several factors, the most obvious being the specific membrane element being tested and the recovery (permeate to feedwater ratio) at which the element was being operated.

Feedwater Chemistry

Initially, the test water used was the same raw water used by CHWA having a TDS of 1900-2000 mg/L. However, after having experienced several problems caused by the relatively high sulfate content (550 mg/L) of this well water, the decision was made to switch to CHWA finished potable water wherein the sulfate concentration was considerably lower (80 mg/L). A typical chemical analysis of the CHWA finished water is presented in Table 1.

Table 1. TYPICAL CHEMICAL ANALYSIS OF FEEDWATER (CHWA POTABLE WATER)

Parameter		
Alkalinity(as $CaCO_3$)	16	mg/L
Calcium	33	mg/L
Chloride	200	mg/L
Conductivity(as mg/L NaCl)	470	mg/L
Fluoride	0.3	mg/L
Magnesium	23	mg/L
Potassium	3.9	mg/L
Silicon	2.6	mg/L
Strontium	7.1	mg/L
Sulfate	80	mg/L
Total Hardness(as $CaCO_3$)	185	mg/L
Total Silica(SiO_2)	5.7	mg/L

The raw water for the CHWA water is drawn from the upper Hawthorn aquifer located approximately 1.5 miles northeast of the CHWA treatment facilities and pretreated with sodium hexametaphosphate and sulfuric acid before entering three two-stage reverse osmosis units. The RO product water is blended with raw water, degasified, chlorinated and stabilized with soda ash before distribution. At this point, the test water was drawn for the research project. CHWA finished water was used in almost all cases except for the radium and uranium tests. The test water for the radium experiments was CHWA raw water containing natural radium. Well water containing naturally occurring uranium was obtained for the uranium tests from a small community in southern Florida.

Feedwater Pretreatment

As shown in Figure 1, the pilot plant test system utilized a recirculation flow pattern with permeate and concentrate flows blended together and returned to the feedwater holding tank. As a result of this, the water required an initial pH adjustment to conform to the operating specifications of the particular membrane element being tested. The proper pH was accomplished by the adding of small amounts of sulfuric acid. Frequently, however, the target pH was exceeded and soda ash was added in order to compensate. Throughout the testing period, the pH tended to drift upward and consequently very small dosages of sulfuric acid were added to maintain the pH goal. Due to the low concentrations of the natural chemical constituents the use of a sequestering agent was not necessary because the solubility products were not exceeded.

Exceptions to the above procedures occurred with two natural waters, containing uranium and radium. The CHWA water containing radium was pumped directly into the feed water holding tank via a tap in the CHWA influent piping and then, in order to remove hydrogen sulfide, was degasified through vigorous recirculation which bypassed the RO module. The well water with natural uranium was collected in a 378.5 L (100 gal) plastic storage tank and transferred to the feedwater holding tank. Both of the waters were then subjected to acid pretreatment for pH adjustment.

Initially, the feedwater was filtered through a 5 micrometer cartridge, upflow filtration unit. Upon spiking the water with mercury, a rapid decline in feed concentration occurred which was thought to be caused by an adsorption of the mercury on the filter cartridges. The filter cartridges were removed from their housing after which time the feedwater concentrations of mercury were considerably more stable. Use of the filters was then discontinued for the remaining test period.

Contaminant Addition

Spiking of the test water with the test contaminants was achieved by weighing out an amount of source material based upon the desired feedwater concentration, mixing it in distilled water and adding the solution to the feedwater holding tank. Mixing was accomplished by direct recirculation of the test water for 30-45 minutes using the RO feed pump (by passing the RO module).

Monitoring Instrumentation

Process and control instrumentation consisted of continuous monitoring of feedwater pH, product flow, concentrate flow, feedwater pressure, product water pressure, and concentrate pressure (Figure 1).

Sampling Ports

Three sampling locations were utilized: one port each for feed, product and concentrate waters (Figure 1).

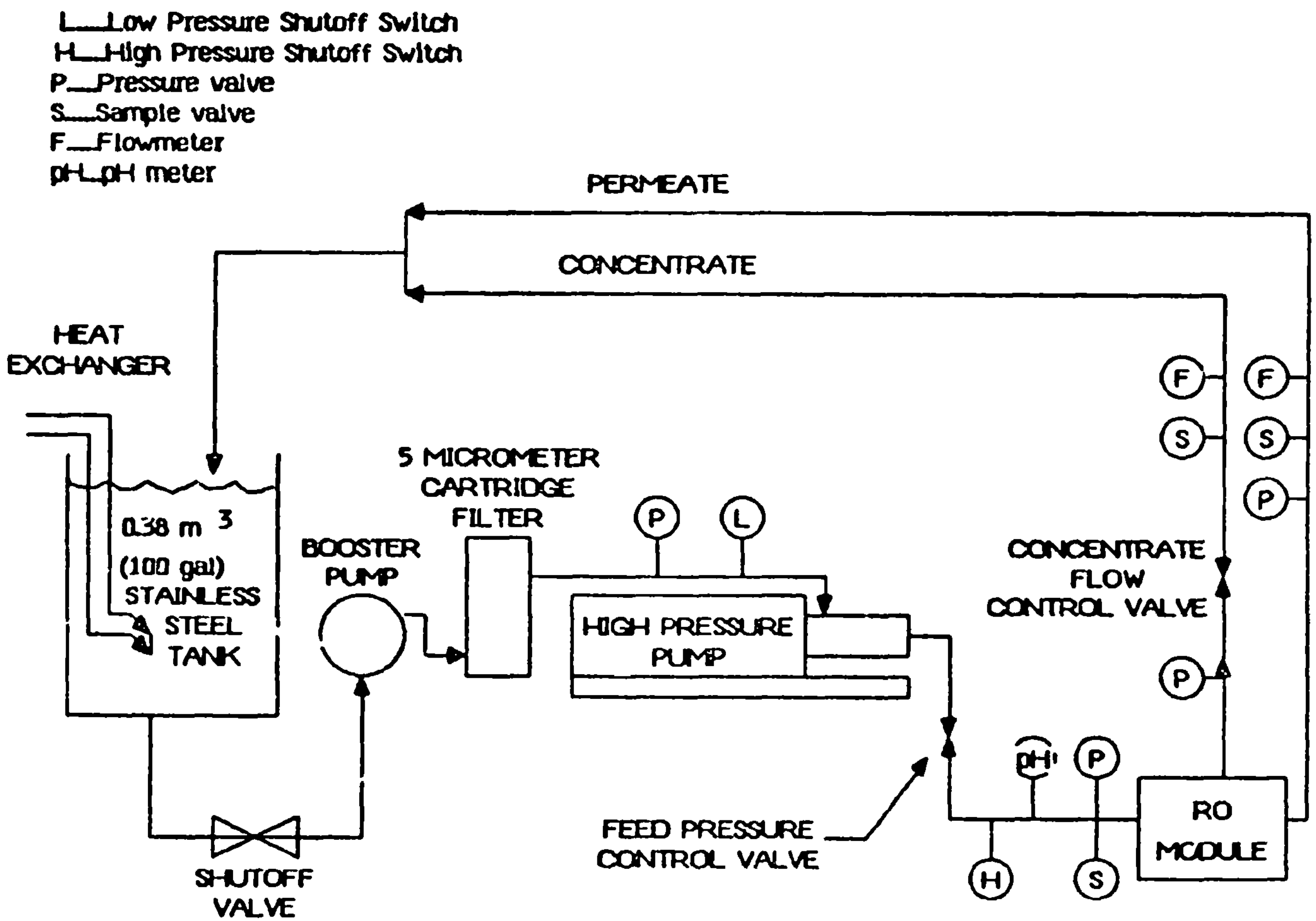

Figure 1. Flow diagram of CHWA 19m^3/day reverse osmosis research units.

SECTION 4

PILOT PLANT EXPERIMENTS AND DATA COLLECTION

SYSTEM OPERATION

Initially, the test water was spiked with one contaminant and the system was operated continuously for 6 to 8 hours per day during the regular 5 day work week. Because this schedule required an inordinate amount of time to complete a full series of tests with all the inorganic contaminants, the decision was made to combine 2 or 3 contaminants and to shorten the run time to permit 3 to 4 test runs daily. Thus, the time required to study a single membrane element was significantly reduced. Each test ran approximately 2.5 hours with continuous cooling of the feedwater. Usually, one hour elapsed between test runs although this time varied according to ambient conditions. After each contaminant group test run, the feedwater holding tank was emptied. Vigorous flushing with fresh water of both the holding tank and the RO module ensued. This water was then pumped to waste and the flushing procedure repeated two more times to ensure complete removal of the contaminants.

Each membrane element was run according to the manufacturer's specifications for the testing of that particular membrane element. Thus, the product water flow rates, feedwater pressures and the specific recoveries differed between membrane elements.

SYSTEM PERFORMANCE DATA

The operation of the RO pilot system was monitored by direct and continuous measurement of feedwater pH and product water and concentrate flows. Pressure guages installed on the feed water, product water and concentrate streams were referenced on an hourly basis during each test run. Performance data were collected immediately prior to test water sample collection. Due to feed water temperature fluctuations, the desired system recovery tended to drift and therefore very frequent fine-tuning of the feed and concentrate flows was necessary.

WATER SAMPLE COLLECTION

Test water samples consisted of feedwater, product water and concentrate; all three were collected at each sampling in the order of product water, concentrate and then feedwater so as not to disturb the system recovery by lowering the feedwater pressure prior to product water and concentrate sampling.

The amount of water sample collected varied according to the analyses to be performed but was generally around one liter. This one liter sample was then split to provide for both in-house analytical work and those analytical procedures conducted by Environmental Quality Laboratory or the U.S. Environmental Protection Agency. EQL provided wide mouth 250 ml polyethylene bottles for their water samples and all samples were preserved utilizing the procedures recommended by the USEPA (6).

CHEMICAL ANALYSES

Routine in-house chemical analyses were performed immediately following sample collection and consisted of pH (Corning pH meter 125), TDS (by conductivity, Myron-L meter), total hardness (EDTA titrimetric method) and chlorides (argentometric method).

Analyses of the spiked inorganic contaminants, e.g. fluoride, nitrate, arsenic, selenium, cadmium, mercury, chromium and lead, were conducted by EQL and or by the USEPA, using USEPA approved procedures (8). Radium, uranium, molybdenum, copper and nitrite nitrogen determinations were exclusively conducted by the USEPA. A list of analyses and analytical methods is shown in Table 2.

QUALITY CONTROL

Both EQL and U.S. EPA analytical laboratories followed standard laboratory QC procedures in conducting analyses of water samples. Quality control samples were run with unknown samples and each laboratory participated in the U.S. EPA performance evaluation studies twice per year.

TEST SCHEDULE

At the beginning, only one contaminant was investigated at a time. This proved too lengthy considering the time available and therefore, the decision was made to test 2 or 3 contaminants concurrently. This arrangement is detailed in Table 3.

Testing of each contaminant or contaminant group was generally conducted for a time to permit the collection of 12 or more samples per test run. Occasionally a test was repeated to verify unrealistic or inconsistent data particularly in the case of mercury where analytical results were quite varied. During the last study with the Hydranautics membrane, several short term tests were added. These tests provided limited data of only 4 - 8 samples.

MEMBRANE ELEMENT OPERATING SPECIFICATIONS

As a general rule the manufacturer's operating specifications were adhered to quite strictly. As a result of this, some variations exist in operating parameters between the membrane elements tested; a listing of operating specifications for each element is shown in Tables 4 to 8.

TABLE 2. LIST OF CHEMICAL ANALYSES AND ANALYTICAL METHODS

Laboratory*	Parameter	Analytical method
CHWA	pH	Corning pH meter 125
CHWA	TDS	Myron L TDS meter (conductivity)
CHWA	Total hardness	Titrimetric, EDTA
CHWA	Chloride	Argentometric
EQL	Fluoride	Potentiometric, ion selective electrode
EQL	Nitrate	Colorimetric, automated cadmium reduction
EQL	Arsenic	AA, graphite furnace
EQL	Selenium	AA, graphite furnace
EQL	Cadmium	AA, flame photometric
EQL	Mercury	AA, manual cold vapor technique
EQL	Chromium	AA, graphite furnace
EQL	Lead	AA, graphite furnace
EPA WERL	Fluoride	Technicon-Alizarin fluorine blue
EPA WERL	Arsenic	AA, graphite furnace
EPA WERL	Selenium	AA, graphite furnace
EPA WERL	Cadmium	AA, graphite furnace >0.2 mg/L: AA, flame photometric
EPA WERL	Mercury	AA, manual cold vapor technique
EPA WERL	Chromium	AA, graphite furnace >0.2 mg/L: AA, flame photometric
EPA WERL	Lead	AA, graphite furnace
EPA WERL	Uranium	Laser induced fluorometry, EPA Method 908.2
EPA WERL	Radium	Radon emanation technique, EPA Method 903.1
EPA WERL	Molybdenum	AA, graphite furnace
EPA WERL	Copper	AA, flame photometric
EPA WERL	Nitrite	Colorimetric, automated cadmium reduction

* CHWA : On-site laboratory at Charlotte Harbor Water Association Reverse Osmosis Water Treatment Plant
EQL : Environmental Quality Laboratory, Port Charlotte, Florida
EPA WERL : United States Environmental Protection Agency, Water Engineering Research Laboratory, Cincinnati, Ohio

TABLE 3. CONTAMINANT GROUPS

Group	Contaminant	Feedwater Concentration (mg/L)	Source
1	Fluoride	8-12	sodium fluoride
2	Arsenic(+3)	1-2	sodium arsenite
	Selenium(+4)	1.5-3	sodium selenite
3	Arsenic(+5)	1.5-3	sodium arsenate
	Selenium(+6)	1.5-3	sodium selenate
	Chromium(+6)	1.5-3	sodium dichromate
4	Lead	1-2	lead nitrate
	Nitrate(as N)	15-25	sodium nitrate
5	Cadmium	3-4	cadmium chloride
	Mercury	0.6	mercuric chloride
	Chromium(+3)	3-4	chromic chloride
6	Uranium	natural	natural
7	Radium	natural	natural
8	Molybdenum	3-5	molybdenum trioxide
9	Copper	3-5	copper sulfate
10	Nitrite(as N)	3-5	sodium nitrite

TABLE 4. TORAY SC 3100 TECHNICAL SPECIFICATIONS

Membrane type	modified cellulose acetate
Membrane configuration	spiral wound
Maximum feedwater pressure	600 psig
Standard feedwater pressure	428 psig
pH range	4 - 7.5
Maximum feedwater temperature	40° C
Standard feedwater temperature	30° C
Maximum chloride concentration	1 ppm
Maximum feed flow rate	11.9 gpm
Maximum recovery	25%

TABLE 5. FILMTEC BW 30-4021 TECHNICAL SPECIFICATIONS

Membrane type	non-cellulosic
Membrane configuration	spiral wound
Maximum operating pressure	200 psig
Recommended initial operating pressure	160 - 180 psig*
Maximum recommended feed flow rate per element	5 gpm
Maximum pressure drop per element	8 psig
Maximum feedwater turbidity	1 ntu
Maximum feedwater temperature	50° C
Recommended feedwater pH range	4 - 10
Antitelescoping device	bonded to element
Dry weight	4 lbs
Nominal diameter	4 in

* This assumes a feedwater temperature of less than 30° C. The recommended operating pressure for temperatures of 30° C to 50° C will be approximately 10 - 20 psig lower.

TABLE 6. DOW RO-5K TECHNICAL SPECIFICATIONS

Membrane type	cellulose triacetate
Membrane configuration	hollow fiber
Maximum operating pressures - feed and brine	450 psig
Maximum feedwater turbidity	1 jtu
Maximum feedwater chlorine concentration	1.0 mg/L
Maximum feedwater temperature	30° C
Recommended feedwater pH range	4 - 7.5
Dimensions - case length	48 in (121.9 cm)
case diameter	6.25 in (15.9 cm)
Shipping weight	86 lbs (39.1 kg)

TABLE 7. DUPONT B-9 MODEL 0440 TECHNICAL SPECIFICATIONS

Membrane type	B-9 aramid
Membrane configuration	hollow fiber
Initial product water capacity*	4200 gpd nominal +15%, -10%
Salt rejection as shipped*	> 90%
Rated operating pressure	400 psig
Temperature range	0 - 35° C
pH range, continuous exposure	4 - 11
Minimum brine rate	3200 gpd
Maximum brine rate	9600 gpd
Shell dimensions - outer diameter	5-1/4 in
inner diameter	4-5/8 in
length	47 in
Shell material	filament wound fiberglass epoxy
End plates	fiberglass epoxy
Snap rings	SAE 1075 carbon steel, cadmium plated
Connections - feed and product	1/2 " female, NPT
brine	3/8 " female, NPT
brine sample	1/8 " female, NPT
Operating position	horizontal or vertical
Permeator weight, filled with water	50 lbs

* Based on operation with a feed of 1500 mg/L sodium chloride at 400 psig, 25° C and 75% conversion, standard test conditions.

TABLE 8. HYDRANAUTICS MODEL P/N 4040-LSY-IFCI TECHNICAL SPECIFICATIONS

Membrane type		
Membrane configuration		spiral wound
Rated initial chloride ion rejection*	average	97.5%
	minimum	95.0%
Rated initial permeate productivity*		1600 gpd
Maximum feed flow to element		18 gpm
Maximum applied pressure		600 psig
Minimum concentrate flow @ rated permeate output		4.9 gpm
Maximum operating temperature		45° C
Feed pH range		4 - 9
Oxidant tolerance		0.0 ppm

* Above ratings are based on a test solution of 2000 ppm sodium chloride at a temperature of 25° C. Under an applied pressure of 270 psig, a water recovery of 10% and a pH of 5 - 6.

SECTION 5

RESULTS

INTRODUCTION

Pilot studies for the removal of the inorganic contaminants were conducted with five different RO modules. The modules are considered state-of-the-art membranes with all being practically applied to treat drinking waters. The primary objective of the study was to obtain RO rejection data for most of the EPA regulated inorganic contaminants and not to compare one membrane against another. Initially this report was planned to be written on a contaminant basis, but because of the rather significant variation in operating conditions, a decision was made to present the data by individual membrane.

Although membrane comparison will naturally be made, the reader should be aware that the membranes were not operated under similar conditions and that comparison of rejection values between the membranes is not totally valid. The purpose of the study therefore was to provide rejection data for comparison of specific contaminant rejection and comparison of these values to the rejection of the more common naturally occurring substances such as sodium, chloride, calcium, etc.

System Operation Performance

The parameters used to evaluate RO system performance are pressure, flow, and water quality. The monitoring instrumentation provided continuous readouts of pressures (feed, product and concentrate) and flows (product and concentrate). The reading from these monitors along with system elapsed operating time, feed water pH and feedwater temperature were recorded each time a set of water samples were collected. Additionally, the TDS of the feed, product and concentrate water samples was measured and recorded.

The system performance information for each membrane element is presented in the discussion of each membrane. Each membrane element was operated according to the manufacturer's specifications and, therefore, significant variation exists between the operating pressures, flows and system recoveries of the membranes.

Natural Constituents

The typical method for evaluating a reverse osmosis membrane is to determine the desalinating capacity, i.e. the ability to reject salts as measured by the difference in TDS in the feed and product streams. Concurrent with inorganic contaminant testing, analyses for several of the common natural constituents in the feedwater were performed to establish baseline system performance criteria by which any problems could be detected as evidenced by a decline in rejection capacity. This testing consisted of TDS, total hardness, and chloride ion determinations for all membrane elements. Sodium and calcium were also analyzed during the testing of the Dupont and Hydranautics elements. A review of these data reveals no major differences in rejection efficiencies for any of the membrane elements tested with percent rejections for all elements varying as follows: TDS (93.8 - 97.6), total hardness (97.7 - 99.3) and chloride ion (91.4 - 94.5). For the Dupont and Hydranautics elements only, the sodium (96 percent) and calcium (98-99 percent) removals were also reported.

The removal data for the natural substances showed in some cases a decline in removal with time. Although the decreases were relatively small, 2-5 percent, these changes were observed and noted. The most significant change occurred in the early stages of the Filmtec test program when TDS rejection declined from about 97 percent to about 87 percent and returned to the original 97 percent.

TORAY MEMBRANE

The first series of tests were conducted with a Toray membrane whose general characteristics are given in Table 4. The system was run for 104 days (620 hrs) at an average feed water pressure of 1960 kPa (284 psig). During the test period of day 1 to day 57, CHWA raw well water (TDS 2000 mg/L) was used as the test water. Because of the high sulfate and some precipitation problems, the test water source was changed to CHWA finished water starting on test day 58. This change was the reason for the decrease in TDS of the feed water from around 2000 mg/L for the first 57 days to 500 - 700 mg/L for the remaining tests.

A summary of the operational data collected is shown in Table 9. A summary of the removal results of the natural occurring substances that were measured, TDS, chloride and hardness, are also shown in Table 10 and the TDS data is plotted in Figures 2 and 3. For the 104 day test period, removals averaged 95 percent for TDS, 98 percent for hardness and 93 percent for chloride.

A summary of the removal values for the spiked contaminants is shown in Table 11. Because of either testing problems or analytical problems, removal data is lacking for Cr+3, Hg, and U.

The test data shows that best removals (97-99 percent) were achieved on cadmium, selenium +4 and +6, arsenic +5, lead and chromium +6. Lower removals (44 - 94 percent) were achieved on fluoride, nitrate and arsenic III. The low removals for arsenic III were verified by repeating the tests several times. A wide variation in removals (44-79 percent) was observed for arsenic +3. Partial oxidation of arsenic +3 to arsenic +5 may have been the reason for this variation.

TABLE 9. SUMMARY OF TORAY MEMBRANE OPERATIONAL DATA

RUN DAYS	1-13	16-33	34-35	36-57	67-71	72-77	78-89	92-97	100-104	AVG DAYS 1-104
FEED WATER SOURCE	A	A	A	A	B	B	B	C	B	
CONTAMINANTS	F	NO_3	As+3	Cd Hg Cr+3	As+3 Se+4	As+3	Pb	U	Cr+6 As+5 Se+6	
SAMPLES/READINGS	26	35	4	46	10	11	20	14	11	--
FEEDWATER pH (units)										
--Average	5.8	5.8	5.8	5.6	5.6	5.6	5.7	--	5.7	5.7
--Minimum	5.5	5.4	5.8	5.1	5.4	5.4	5.2	--	5.4	5.4
--Maximum	6.3	6.3	5.9	6.0	6.0	6.0	6.1	--	6.1	6.1
FEEDWATER TEMP (C°)										
--Average	39	38	--	37	32	32	34	32	33	35
--Minimum	32	35	--	24	27	25	28	20	23	27
--Maximum	46	47	--	45	39	38	39	41	41	42
FEEDWATER PRESSURE (PSIG)										
--Average	261	260	--	271	287	295	292	299	309	284
--Minimum	250	255	--	250	275	290	275	280	290	271
--Maximum	285	270	--	295	295	300	300	320	350	302
FEEDWATER FLOW (GPM)										
--Average	6.9	6.8	--	6.8	6.8	6.6	6.5	6.7	6.6	6.7
--Minimum	6.3	6.6	--	7.1	6.6	6.5	6.3	6.5	5.9	6.5
--Maximum	7.0	7.0	--	6.1	7.0	6.7	6.7	7.0	6.9	6.8
RECOVERY (percent)										
--Average	10.6	9.5	--	9.7	9.6	10.0	10.3	9.2	8.8	9.8
--Minimum	9.3	8.2	--	8.0	8.3	8.8	9.0	7.3	6.5	8.3
--Maximum	12.9	11.5	--	11.5	11.1	11.4	12.4	10.9	10.2	11.5

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water With Natural U

TABLE 10. SUMMARY OF TORAY MEMBRANE TEST DATA

RUN DAYS	1-15	16-33	34-35	36-57	67-71	72-77	78-89	92-97	100 - 104	AVG
SOURCE OF WATER	A	A	A	A	B	B	B	C	B	
CONTMINANTS	F	NO_3	As+3	Cd Hg Cr+3	As+3 Se+4	As+3	Pb	U	Cr+6 As+5 Se+6	DAYS 1-104
SAMPLES/READINGS	26	35	4	46	10	11	20	--	11	--
FEEDWATER CONC (mg/L)										
TDS - AVG	1988	2059	2063	1913	672	877	920	--	438	--
TDS - MIN	1800	1875	1975	1700	525	825	675	--	410	--
TDS - MAX	2225	2250	2100	2100	850	950	1150	--	460	--
HARDNESS - AVG	609	624	645	625	198	--	285	--	115	--
HARDNESS - MIN	580	550	610	540	180	--	170	--	100	--
HARDNESS - MAX	660	720	660	760	210	--	390	--	120	--
CHLORIDE - AVG	651	661	680	613	225	279	287	--	176	--
CHLORIDE - MIN	600	570	655	550	214	260	228	--	160	--
CHLORIDE - MAX	730	720	690	685	246	300	330	--	200	--
PERCENT REMOVAL										
TDS - AVG	95	94	94	94	96	96	97	--	96	95
TDS - MIN	94	94	94	94	95	96	96	--	95	95
TDS - MAX	96	95	94	95	97	97	97	--	97	96
HARDNESS - AVG	99	98	98	98	98	--	99	--	99	99
HARDNESS - MIN	98	97	98	98	97	--	99	--	99	98
HARDNESS - MAX	99	99	98	99	99	--	99	--	99	99
CHLORIDE - AVG	93	93	93	93	92	94	94	--	92	93
CHLORIDE - MIN	92	92	92	92	90	93	93	--	89	92
CHLORIDE - MAX	94	94	93	94	93	94	94	--	94	94

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

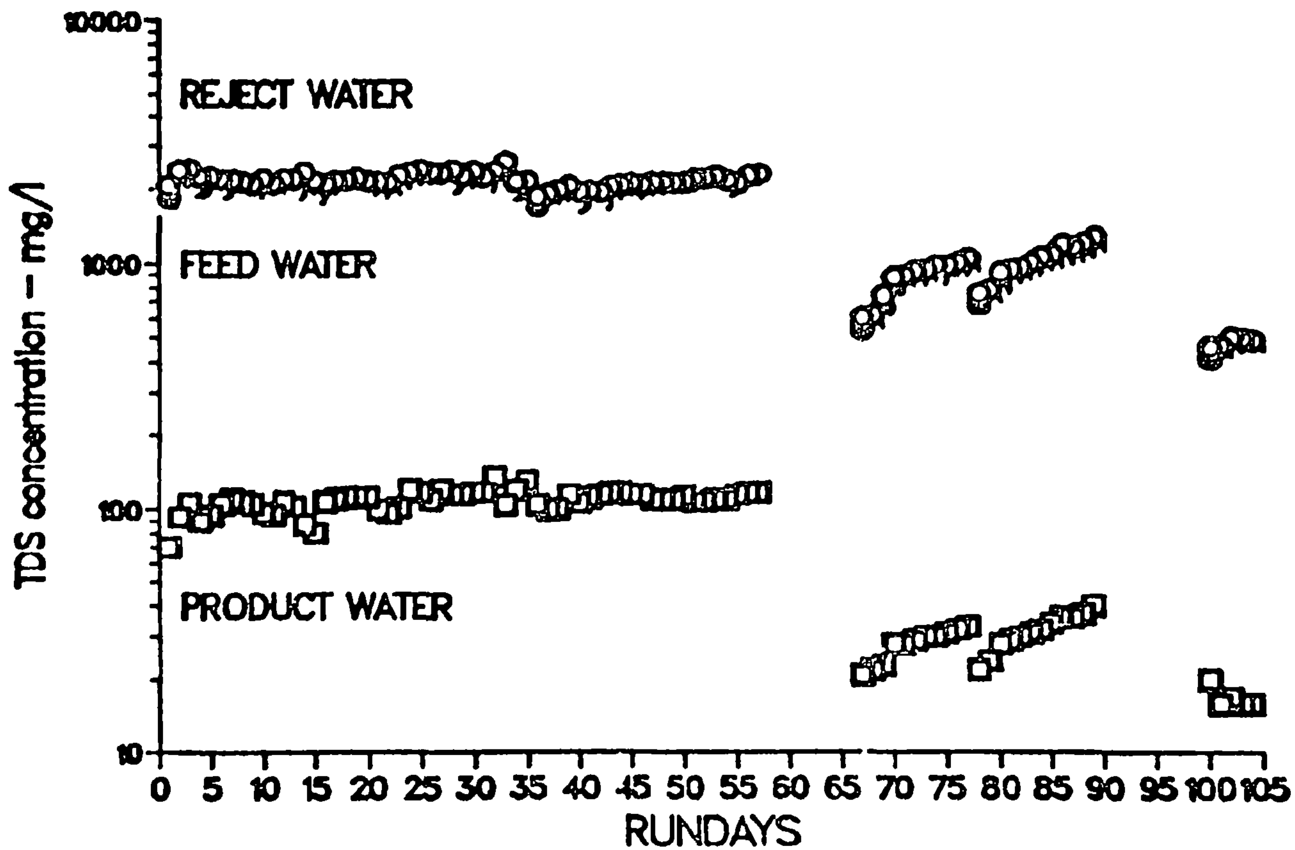

Figure 2. Removal of TDS with Toray membrane.

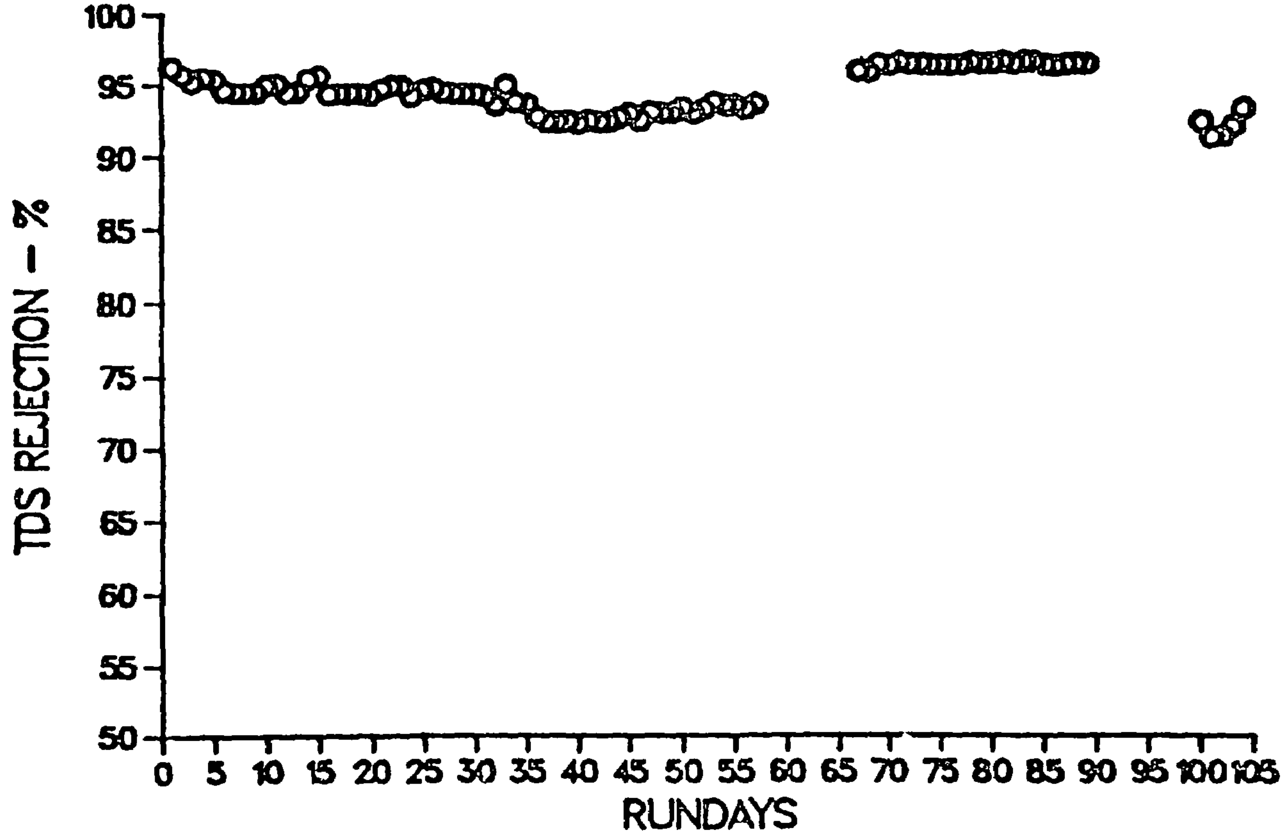

Figure 3. Rejection (percent) of TDS with Toray membrane.

TABLE 11. SUMMARY OF CONTAMINANT REMOVAL WITH TORAY MEMBRANE

Run Days	Contaminant	Samples No.	Feedwater Concentration—mg/L Min	Max	Avg	Percent Rejection Min	Max	Avg
1-13	F	26	3.0	10.0	6.1	73	94	90
16-32	NO_3(N)	35	1.7	25.3	11.8	35	82	69
34-35	As(+3)	4	0.03	0.34	0.14	58	70	63
36-57	Cd	46	0.02	0.54	0.23	95	99	99
	Hg	0	-	-	-	-	-	-
	Cr(+3)	0	-	-	-	-	-	-
67-71	As(+3)	10	0.03	0.68	0.30	44	79	66
	Se(+4)	10	0.12	0.74	0.33	96	99	97
72-77	As(+3)	11	0.15	0.68	0.30	46	76	64
78-89	Pb	12	0.24	1.3	0.55	97	99	98
92-97	U	—	—	—	—	—	—	—
100-104	Cr(+6)	6	0.31	0.96	0.60	97	98	97
	As(+5)	12	0.12	0.74	0.35	97	>99	99
	Se(+6)	12	0.26	1.0	0.61	99	>99	>99

FILMTEC MEMBRANE

The second test series was conducted with a Filmtec membrane whose description is given in Table 5. The test period lasted for 74 days (929 hrs) and the feed water pressure averaged 1318 kPa (191 psig). Thus, the operating pressure averaged about 950 kPa (100 psig) less than the average for the Toray membrane test.

A summary of the operational data for a 74 day test period is shown in Table 12. The rejection results of the natural substances measured (TDS, chloride, hardness) are given in Table 13 and the rejection results of TDS are plotted in Figures 4 and 5. Removal averaged 95 percent for TDS, 98 percent for hardness and 92 percent for chloride.

The TDS data in Figure 5 shows a steady decrease in TDS rejection from about day 9 (97%) through day 37 (84%) and then a return to the initial rejection value (97%) day 39. The reason for this decrease is not known, but this decline suggests some type of an operation problem.

A summary of the rejection data for the spiked contaminants and along with natural uranium is shown in Table 14. The results were somewhat similar to the Toray membrane results with highest removals (95 - 98%) achieved on arsenic +5, selenium +4 and +6, chromium +3 and +6, lead, cadmium, and uranium. Lower removals were obtained with fluoride, nitrate, arsenic +3 and mercury. The widest variation between minimum and maximum removals were experienced with arsenic +3 as had also occurred with the Toray tests. Oxidation of some arsenic +3 to arsenic +5 is again suggested as a possible cause for this wide variation in removals.

DOW MEMBRANE

The Dow membrane was the third membrane tested. The test period lasted 72 days (760 hrs) and the average feed pressure was 1911 kPa (277 psig).

A summary of the operational data collected is shown in Table 15. This membrane had the highest percent recovery (55 - 60) of the five membranes tested. The rejection data from the natural elements (TDS, chloride, hardness) are shown in Table 16 and the rejection data for TDS is plotted in Figures 6 and 7. TDS rejection averaged 96 percent through the 72 days. Figure 7 shows, however, that for the period, day 13 - 25, that TDS rejection decreased from about 97 percent to 94 percent and then returned to around 96 percent for the duration of the test period. Why this slight decrease occurred is not known. Removals for hardness was 98 percent and for chloride, 93 percent.

A summary of removal of spiked contaminants and for uranium and radium is shown in Table 17. The pattern of removals was similar to that of the first two membranes. Best removals (95 - 99 percent) were achieved on lead, cadmium, chromium +3 and +5, arsenic +5, selenium +4 and +6, uranium and radium. Lower removals were achieved with fluoride, nitrate, arsenic +3 and mercury. Some questions exist on mercury removals because of analytical problems and adsorption within the system. However, two different test

TABLE 12. SUMMARY OF FILMTEC MEMBRANE OPERATIONAL DATA

RUN DAYS	1-10	11-20	21-37	38-49	50-62	63-66	67-70	71-74	AVG
SOURCE OF WATER	B	B	B	B	B	B	B	C	
CONTAMINANTS	F	As-3 Se+4	NO_3 Pb	As+5 Se+6 Cr+6	Cd Hg Cr+3	NO_3 Pb	Cd Cr+3	U	DAYS 1-74
SAMPLES/READINGS	22	21	32	16	21	8	9	7	--
FEEDWATER pH (UNITS)									
-AVG	6.8	6.9	7.2	6.3	6.4	6.7	5.5	7.7	6.7
-MIN	5.7	5.7	6.8	5.2	6.0	6.3	5.2	7.5	6.0
-MAX	7.1	7.4	7.5	7.0	6.8	6.8	5.6	7.8	7.0
FEEDWATER TEMP (C)									
-AVG	27	32	27	29	28	24	31	31	29
-MIN	17	22	20	20	17	14	20	24	19
-MAX	36	45	38	43	37	28	36	50	39
FEEDWATER PRESSURE (PSIG)									
-AVG	180	185	202	196	194	191	181	196	191
-MIN	165	160	180	170	185	175	180	185	175
-MAX	210	200	220	220	210	200	190	200	206
FEEDWATER FLOW (GPM)									
-AVG	3.7	3.0	3.2	4.2	4.1	4.6	4.5	4.3	4.0
-MIN	3.5	2.2	2.6	2.8	3.3	4.6	4.4	4.2	3.5
-MAX	3.8	3.4	3.6	4.6	5.1	4.7	4.5	4.5	4.3
RECOVERY (%)									
-AVG	9.8	12.0	8.1	8.5	11.8	10.2	12.1	10.9	10.4
-MIN	6.6	7.8	6.2	4.5	6.4	7.7	9.0	8.6	7.1
-MAX	14.7	20.9	10.9	15.9	18.1	11.8	13.2	13.8	14.9

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water With Natural U

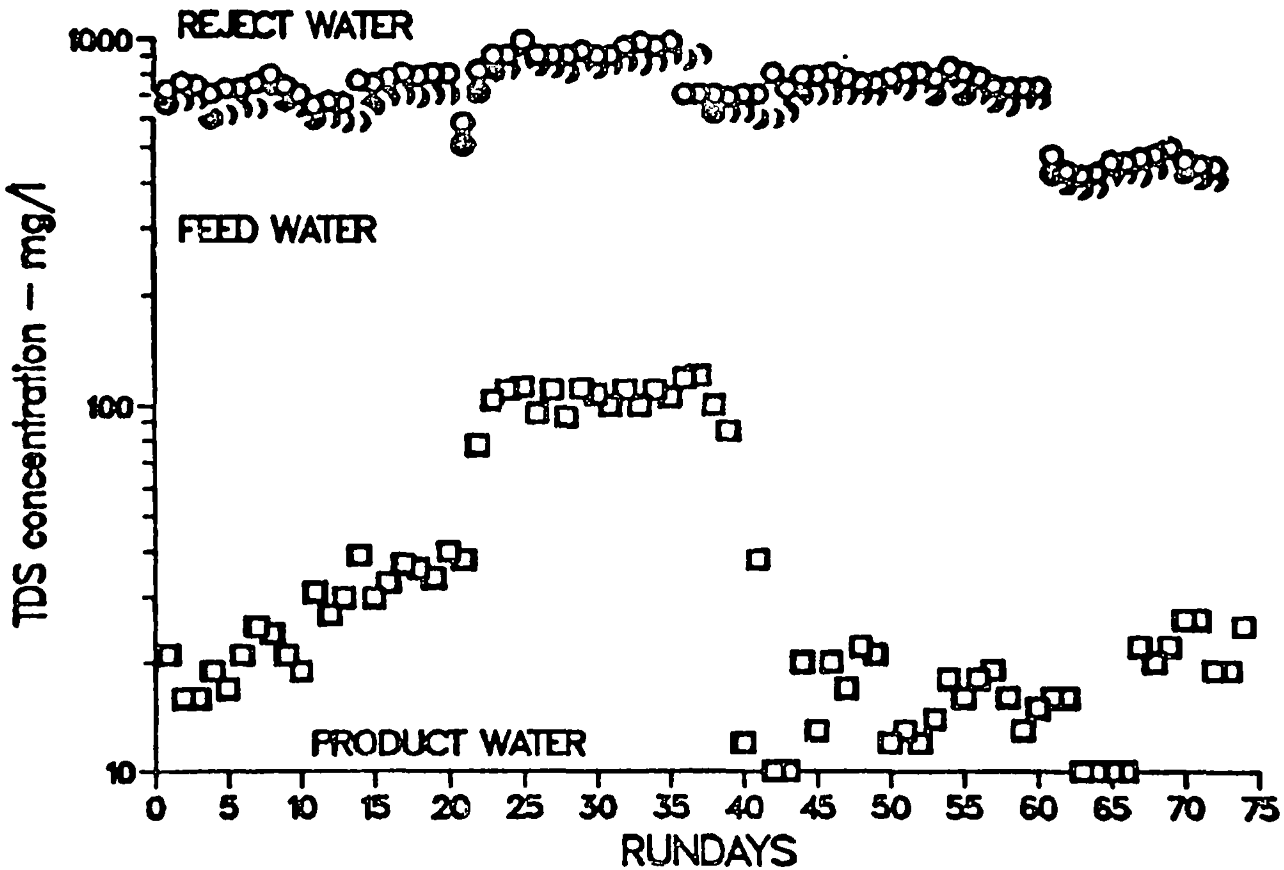

Figure 4. Removal of TDS with Filmtec membrane.

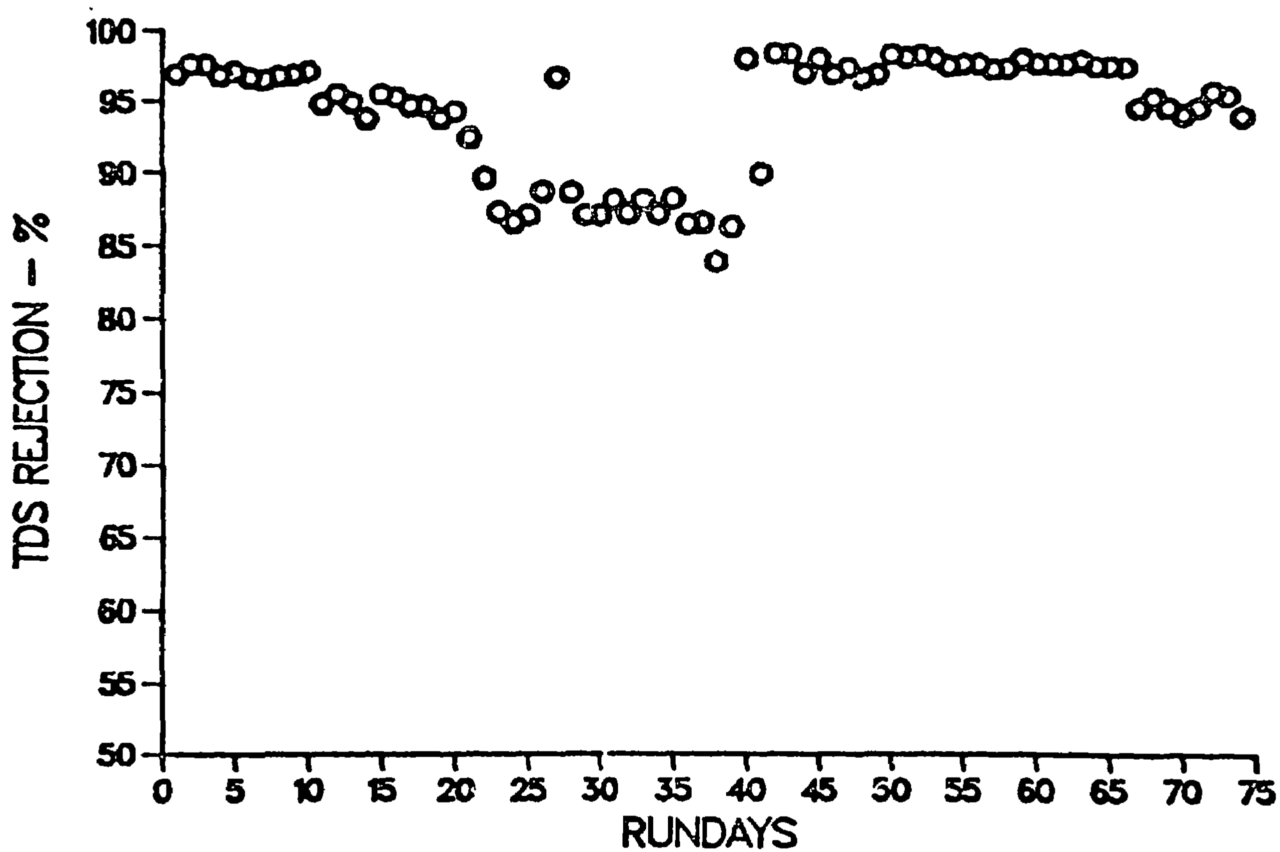

Figure 5. Rejection (percent) of TDS with Filmtec membrane.

TABLE 13. SUMMARY OF FILMTEC MEMBRANE TEST DATA

RUN DAYS	1-10	11-20	21-37	38-49	50-62	63-66	67-70	71-74	AVG DAYS
FEED WATER SOURCE	B	B	B	B	B	B	B	C	--
CONTAMINANTS	F	As+3 Se+4	NO_3 Pb	As+5 Se+6 Cr+6	Cd Hg Cr+3	NO_3 Pb	Cd Cr+3	U	1-74 --
SAMPLES/READINGS	22	21	32	16	21	8	9	7	--
FEED CONC. (mg/L)	669	648	810	664	702	393	420	420	--
TDS - AVG	600	575	500	600	650	380	410	400	--
TDS - MIN	800	700	900	725	775	420	735	470	--
TDS - MAX									
HARDNESS-AVG	327	250	155	155	148	91	102	145	--
MIN	310	230	130	140	130	65	85	130	--
MAX	340	260	260	180	160	100	110	170	
CHLORIDE-AVG	224	324	293	234	223	164	185	133	--
MIN	200	280	230	225	200	160	175	125	--
MAX	255	360	320	245	240	170	200	140	--
PERCENT REMOVAL									
TDS - AVG	97	95	88	96	98	98	95	95	95
TDS - MIN	96	92	85	84	97	97	94	92	92
TDS - MAX	98	96	93	99	98	98	96	96	97
HARDNESS - AVG	99	98	94	99	99	99	99	99	98
MIN	98	97	86	94	99	99	99	99	96
MAX	99	99	98	99	99	99	99	99	99
CHLORIDE - AVG	93	91	88	93	94	94	92	89	92
MAX	90	87	85	81	92	93	90	85	88
MIN	95	94	91	96	96	96	94	91	94

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

TABLE 14. SUMMARY OF CONTAMINANT REMOVAL WITH FILMTEC MEMBRANE

RUN DAYS	CONTAMINANT	SAMPLES (NO.)	FEEDWATER CONCENTRATION - mg/L Min	Max	Avg	Percent Rejection Min	Max	Avg
1-10	F	22	8.4	10.2	8.9	72	92	83
11-20	As(+3)	7	0.04	0.18	0.10	55	83	69
	Se(+4)*	21	0.02	0.08	0.04	>85	>96	--
21-37	NO_3(N)	20	12.8	14.3	13.7	71	78	75
	Pb	32	0.04	0.13	0.07	65	94	89
39-49	As(+5)	5	0.10	0.47	0.26	98	>99	99
	Se(+6)	16	0.58	2.6	1.2	96	>99	99
	Cr(+6)	9	0.04	1.3	0.73	87	>99	97
50-62	Cd	11	0.28	0.36	0.32	>99	>99	>99
	Hg	10	0.002	0.109	0.040	60	89	78
	Cr(+3)	0	--	--	--	--	--	--
63-66	NO_3(N)	0	--	--	--	--	--	--
	Pb	8	0.19	1.32	0.41	78	>99	97
67-70	Cd	9	2.5	2.6	2.6	99	>99	99
	Hg	0	--	--	--	--	--	--
	Cr(+3)	9	0.05	0.29	0.12	94	98	96
71-74	U	7	0.533	0.879	0.682	99	99	99

*Product water concentrations all less than detectable limit of 0.005 mg/L

TABLE 15. SUMMARY OF DOW MEMBRANE OPERATIONAL DATA

RUN DAYS	1-17	18-26	27-34	34-41	42-50	51-63	64-67	68-69	70-71	72-73	AVG DAYS 1-73
SOURCE OF WATER	B	B	B	B	B	C	B	B	B	B	
CONTAMINANTS	F	NO_3	Cd	As+5	As+3	U	Hg	Ra	Hg	As+3	--
	--	Pb	Hg	Se(+6)	Se+4	--	--	--	--	--	--
	--	--	Cr+3	Cr+6	--	--	--	--	--	--	--
SAMPLES/READINGS	29	19	21	16	24	22	6	2	2	2	--
FEED WATER pH (UNITS)											
--AVG	6.3	6.2	6.0	5.6	4.9	7.6	6.7	7.5	6.3	6.1	6.3
--MIN	4.0	5.6	5.5	5.0	4.5	7.2	6.6	7.4	6.2	6.1	5.8
--MAX	7.4	6.4	6.5	6.4	5.1	6.0	6.8	7.5	6.3	6.1	6.7
FEED WATER TEMP (C)											
--AVG	23	25	25	25	26	25	34	19	19	19	24
--MIN	17	23	20	20	21	22	31	16	19	19	21
--MAX	27	27	30	35	28	35	36	20	19	19	28
FEED WATER PRESSURE (PSIG)											
--AVG	261	261	266	262	263	272	253	295	320	320	277
--MIN	250	250	240	225	245	230	240	290	320	320	261
--MAX	275	270	290	285	305	280	260	300	320	320	290
FEED WATER FLOW (GPM)											
--AVG	6.6	6.9	5.8	5.9	5.7	6.1	6.9	6.0	6.8	6.8	6.3
--MIN	6.2	6.8	5.6	5.7	5.3	5.9	6.8	5.9	6.8	6.8	6.2
--MAX	7.0	7.0	6.0	6.2	6.6	6.3	7.0	6.0	6.8	6.8	6.6
RECOVERY (%)											
--AVG	55.3	56.2	61.8	60.5	64.1	60.4	61.8	55.4	55.8	55.5	58.7
--MIN	53.7	54.4	58.6	57.8	58.7	58.3	59.4	54.2	55.8	55.5	56.6
--MAX	59.6	57.9	65.0	64.9	65.4	65.0	66.1	56.6	55.8	55.5	61.2

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

TABLE 16. SUMMARY OF DOW MEMBRANE TEST DATA

RUN DAYS	1-17	18-26	27-34	34-41	42-50	51-63	64-67	68-69	70-71	72-73	AVG DAYS 1-73
SOURCE OF WATER	B	B	B	B	B	C	B	A	B	B	--
CONTAMINANTS	F	NO_3	Cd	As+5	As+3	U	Hg	Ra	Hg	As+3	--
	--	Pb	Hg	Se(+6)	Se+4	--	--	--	--	--	--
	--	--	Cr+3	Cr+6	--	--	--	--	--	--	--
SAMPLES/READINGS	29	19	21	16	24	22	6	2	2	2	--
FEED WATER CONC (mg/L)											
TDS - AVG	627	6.1	630	625	702	443	625	1763	800	800	--
TDS - MIN	550	575	620	600	650	350	625	1750	800	800	--
TDS - MAX	750	775	640	650	750	600	625	1775	800	800	--
HARDNESS - AVG	139	126	178	161	172	160	148	480	209	205	--
HARDNESS - MIN	120	120	165	150	150	100	140	480	208	200	--
HARDNESS - MAX	160	150	185	180	200	270	150	480	210	210	--
CHLORIDE - AVG	219	203	233	225	263	131	235	535	250	225	--
CHLORIDE - MIN	205	185	220	215	240	125	235	530	250	225	--
CHLORIDE - MAX	225	220	245	233	275	135	235	540	250	225	--
PERCENT REMOVAL											
TDS - AVG	97	95	97	97	96	97	95	96	97	97	96
TDS - MIN	95	94	96	96	96	96	95	96	97	97	96
TDS - MAX	98	96	97	97	96	97	95	95	97	97	96
HARDNESS - AVG	98	96	96	98	98	98	97	98	99	99	98
HARDNESS - MIN	96	94	96	98	97	98	97	98	99	99	97
HARDNESS - MAX	99	98	98	99	98	99	97	98	98	99	98
CHLORIDE - AVG	94	93	93	93	94	91	92	94	94	94	93
CHLORIDE - MIN	93	92	92	91	92	90	92	94	94	94	92
CHLORIDE - MAX	95	94	94	95	94	92	93	95	94	94	94

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

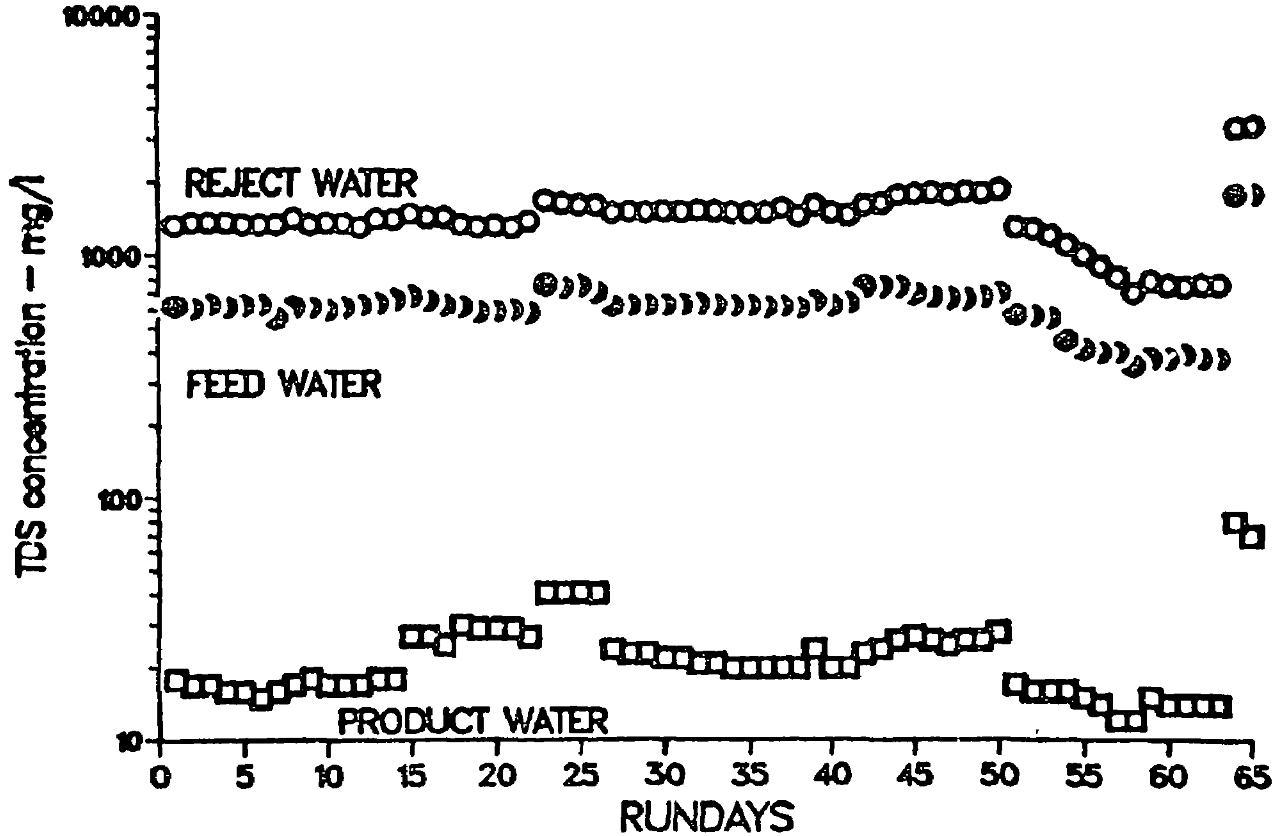

Figure 6. Removal of TDS with Dow membrane.

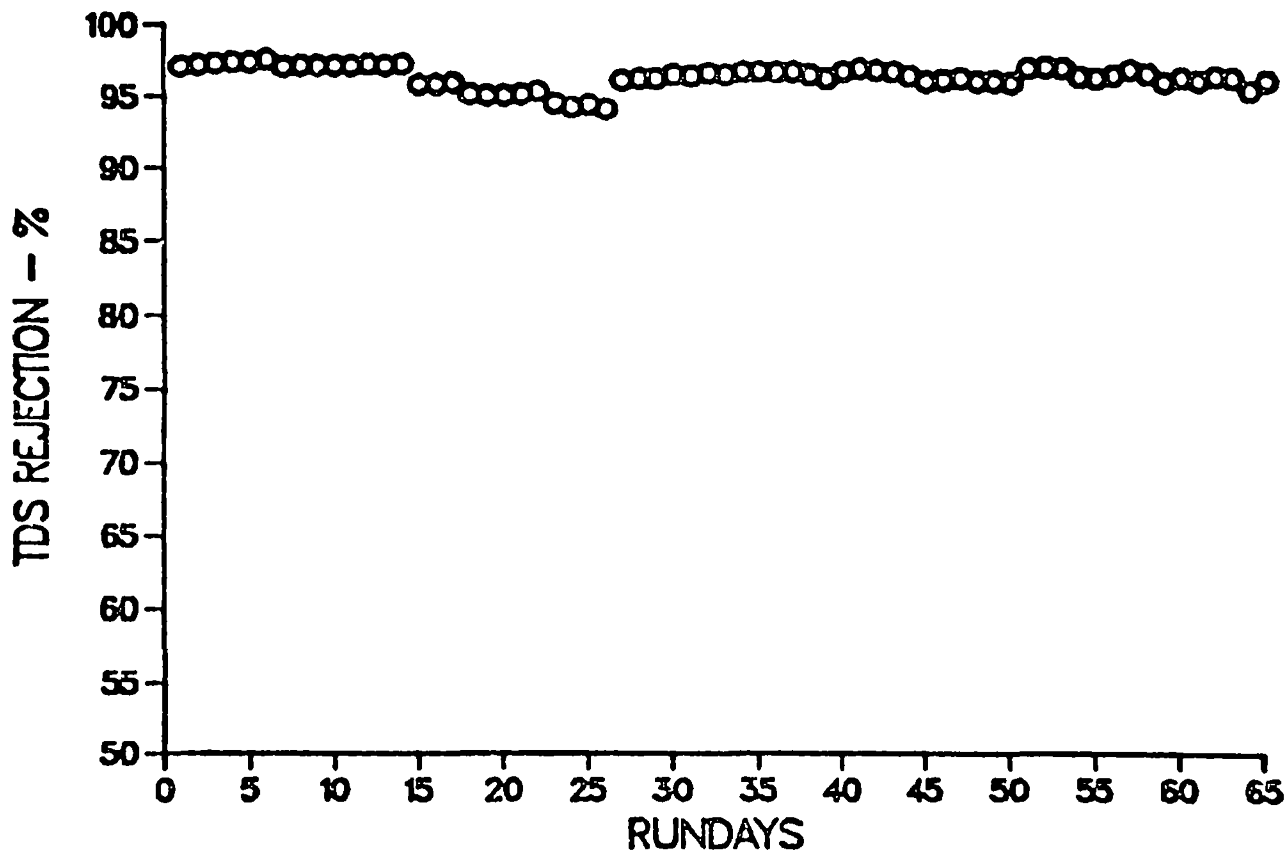

Figure 7. Rejection (percent) of TDS with Dow membrane.

TABLE 17. SUMMARY OF CONTAMINANT REMOVAL WITH DOW MEMBRANE

RUN DAYS	CONTAMINANT	SAMPLE NOS.	FEEDWATER CONCENTRATION - mg/L Min	Max	Avg	PERCENT REJECTION Min	Max	Avg
1-17	F	29	5.5	14.5	8.4	56	97	91
18-26	NO_3(N)	17	12.0	41.4	28.0	82	86	85
	Pb	18	0.09	1.0	0.60	94	98	96
27-34	Cd	21	1.1	3.7	2.2	98	98	98
	Hg	9	0.508	0.636	0.557	12	17	14
	Cr(+3)	21	0.06	1.3	0.49	95	98	97
34-41	As(+5)	16	0.47	1.9	1.1	98	99	98
	Se(+6)	16	1.4	3.3	2.1	99	99	98
	Cr(+6)	16	1.1	3.6	2.0	95	97	96
42-50	As(+3)	11	0.36	0.41	0.39	97	99	98
	Se(+4)	11	0.51	0.65	0.56	98	99	99
	As(+3)	13	1.1	1.3	1.2	73	78	75
	Se(+4)	13	1.4	1.9	1.7	97	99	98
51-63	U	22	0.330	1.650	0.670	98	99	99
64-67	Hg	6	0.0002	0.010	0.003	52	81	64
68-69	Ra(pCi/L)	1	5.05	5.05	5.05	97	97	97
70-71	Hg	2	0.071	0.081	0.076	10	22	16
72-73	As(+3)	2	0.73	0.85	0.79	82	84	83

periods showed very low removals of 10 - 20 percent, the lowest of all the rejection values.

DUPONT MEMBRANE

The fourth membrane evaluated was a Dupont membrane. The test period was 43 days (327 hrs) and the average feed water pressure was 2650 kPa (384 psig), the highest of all the tests conducted. The percent recovery for this membrane was about 50 percent.

A summary of the operational data is shown in Table 18. A summary of the removals of the natural elements (TDS, chloride, hardness, calcium and sodium) is given in Table 19. Rejection data for TDS for the test period is also plotted in Figures 8 and 9. Although TDS rejection was high, 96-99 percent, a slight decline was observed during the test period from the initial high rejection of 99 percent to the 96 percent rejection during the last few days. Again no reason, except for membrane usage, is offered to explain the slight decline. Hardness removals averaged 99 percent and chloride 94 percent.

A summary of the removal for the spiked contaminants and uranium and radium is shown in Table 20. For the most part, the same pattern of removal results existed. Highest removals were achieved on lead, cadmium, chromium +3 and +6, selenium +4 and +6, arsenic +5, uranium and radium. Lower removals were obtained on fluoride, nitrate, arsenic +3 and mercury. The or major difference existed for mercury where removal ranged from 65 - 98 percent which was significantly higher than the 15 - 20 percent removal with the Dow membrane. Because of some analytical uncertainty and observed adsorption with the system, some doubts exist on the validity of all the mercury data.

HYDRANAUTICS MEMBRANE

The last membrane to be studied was the Hydranautics membrane. This membrane was tested for the shortest period of time, only 29 days (303 hrs). The feed water pressure averaged 1953 kPa (283 psig) and percent recovery was around 11 percent.

A summary of the operational data is shown in Table 21. A summary of the removals for the natural substances in the feed water (TDS, chloride, hardness, calcium, sodium) is also shown in Table 22. The TDS rejection data for the test period is plotted in Figures 10 and 11. Once again the TDS rejection data showed a slight decrease with time as the average rejection went from about 99 percent (days 1-5) to around 95 percent (days 26-29). General usage again is suggested as the only explanation for the decrease. Hardness removal averaged 96 percent and chloride 95 percent.

A summary of the removal data for the spiked contaminants and for uranium and radium is shown in Table 23. As reported with all other membranes, highest removals (95 - 99 percent) were achieved with lead, cadmiun, chromium

+3 and +6, selenium +4 and +6, arsenic +5, uranium and radium. Lower removals were obtained on arsenic +3. However, for the first and only time high removals were achieved on fluoride (98 percent) and for nitrate (97 percent). Why these removals were significantly different from the other membrane results is not known.

For the first time, tests were conducted for the removal of nitrite copper, and molybdemum. Although the tests were short, 2 - 3 days, the removal data (average) showed high removals for all three substances; greater than 92 percent for nitrite, 97 percent for copper, and greater than 97 percent for molybdemum.

TABLE 18. SUMMARY OF DUPONT MEMBRANE OPERATIONAL DATA

RUN DAYS	1-5	6-10	11-16	17-22	23-28	29-34	34-35	36-41	42-43	AVG DAYS 1-43
SOURCE OF WATER	B	B	B	B	B	B	A	C	B	
CONTAMINANTS	F	Cd	As+5	Pb	NO_3	As+3	Ra	U	No_3	--
	--	Hg	Se+6	--	--	Se+4	--	--	--	--
		Cr+3	Cr+6	--	--	--				
SAMPLES/READINGS	14	14	17	15	13	16	2	15	2	--
FEED WATER pH (UNITS)										
--AVG	6.2	5.9	6.0	5.3	5.2	5.8	5.5	8.8	5.5	5.8
--MIN	6.1	5.2	5.7	5.1	5.0	5.6	5.5	7.9	5.5	5.8
--MAX	6.6	7.5	6.2	5.4	5.4	6.4	5.5	9.3	5.5	6.0
FEED WATER TEMP(C)										
--AVG	23	24	27	24	27	24	25	26	27	25
--MIN	16	23	18	21	23	21	24	22	26	21
--MAX	33	27	35	32	29	27	25	29	27	30
FEED WATER PRESSURE (PSIG)										
--AVG	379	377	383	395	378	385	383	393	390	384
--MIN	330	350	285	370	360	375	380	385	390	360
--MAX	400	395	400	400	400	395	385	405	390	395
FEED WATER FLOW (GPM)										
--AVG	4.5	4.5	4.6	4.5	4.5	4.5	4.4.	4.4	4.4	4.5
--MIN	4.2	4.4	4.4	4.3	5.2	4.4	4.4	4.4	4.4	4.3
--MAX	4.7	4.9	5.2	5.1	5.0	4.6	4.4	4.4	4.4	4.6
RECOVERY (%)										
--AVG	50.0	48.8	50.2	49.7	50.8	50.5	50.0	50.0	50.0	50.0
--MIN	47.6	44.4	48.8	47.7	50.0	50.0	50.0	50.0	50.0	48.8
--MAX	52.1	50.0	52.1	51.1	52.3	52.1	50.0	50.0	50.0	51.0

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

TABLE 19. SUMMARY OF DUPONT MEMBRANE TEST DATA

RUN DAYS	1-5	6-10	11-16	17-22	23-28	29-34	34-35	36-41	42-43	AVG DAYS 1-43
SOURCE OF WATER	B	B	B	B	B	B	A	C	B	—
CONTAMINANTS	F	Cd	As+5	Pb	NO_3	As+3	Ra	U	NO_3	—
	—	Hg	Se+6	—	—	Se+4	—	—	--	--
	—	Cr+3	Cr+6	--	—	--	--	--	--	--
SAMPLES/READINGS	14	14	17	15	13	16	2	15	2	—
FEED WATER CONC (mg/L)										
TDS-AVG	793	946	765	813	810	867	1700	760	800	—
TDS-MIN	775	925	750	800	800	850	1700	750	800	—
TDS-MAX	800	975	775	825	825	875	1700	774	800	—
HARDNESS-AVG	160	222	160	204	200	215	480	274	200	—
HARDNESS-MIN	160	210	160	200	190	205	480	260	200	—
HARDNESS-MAX	165	240	160	210	205	220	480	285	200	—
CHLORIDE-AVG	233	289	230	249	247	267	533	149	238	—
CHLORIDE-MIN	230	280	220	240	240	255	520	140	230	—
CHLORIDE-MAX	240	305	235	265	255	275	545	160	245	—
CALCIUM-AVG	27	38	26	31	—	34	88	60	--	—
CALCIUM-MIN	27	37	25	28	—	31	86	57	—	--
CALCIUM-MAX	28	39	28	32	—	35	89	62	--	—
SODIUM-AVG	114	128	109	130	—	115	262	68	—	--
SODIUM-MIN	106	109	103	122	—	105	260	56	--	—
SODIUM-MAX	120	136	113	136	—	129	263	76	—	--
PERCENT REMOVAL										
TDS-AVG	99	98	98	98	98	98	96	97	98	98
TDS-MIN	99	98	97	98	98	97	96	96	98	98
TDS-MAX	99	99	99	98	98	98	97	97	98	98
HARDNESS-AVG	99	99	99	99	99	99	99	99	99	99
HARDNESS-MIN	99	89	99	99	99	99	99	99	99	99
HARDNESS-MAX	99	100	99	100	99	100	99	100	100	99
CHLORIDE-AVG	96	96	95	93	93	94	95	93	93	94
CHLORIDE-MIN	96	96	94	95	92	93	95	92	93	94
CHLORIDE-MAX	97	97	96	95	95	94	95	94	93	95
CALCIUM-AVG	98	99	98	98	—	99	99	99	—	99
CALCIUM-MIN	98	99	98	98	—	99	99	99	—	99
CALCIUM-MAX	98	99	98	98	—	99	99	99	—	99
SODIUM-AVG	98	97	96	96	—	96	95	94	—	96
SODIUM-MIN	97	88	95	86	—	94	94	89	—	92
SODIUM-MAX	98	98	98	97	—	97	95	96	—	97

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

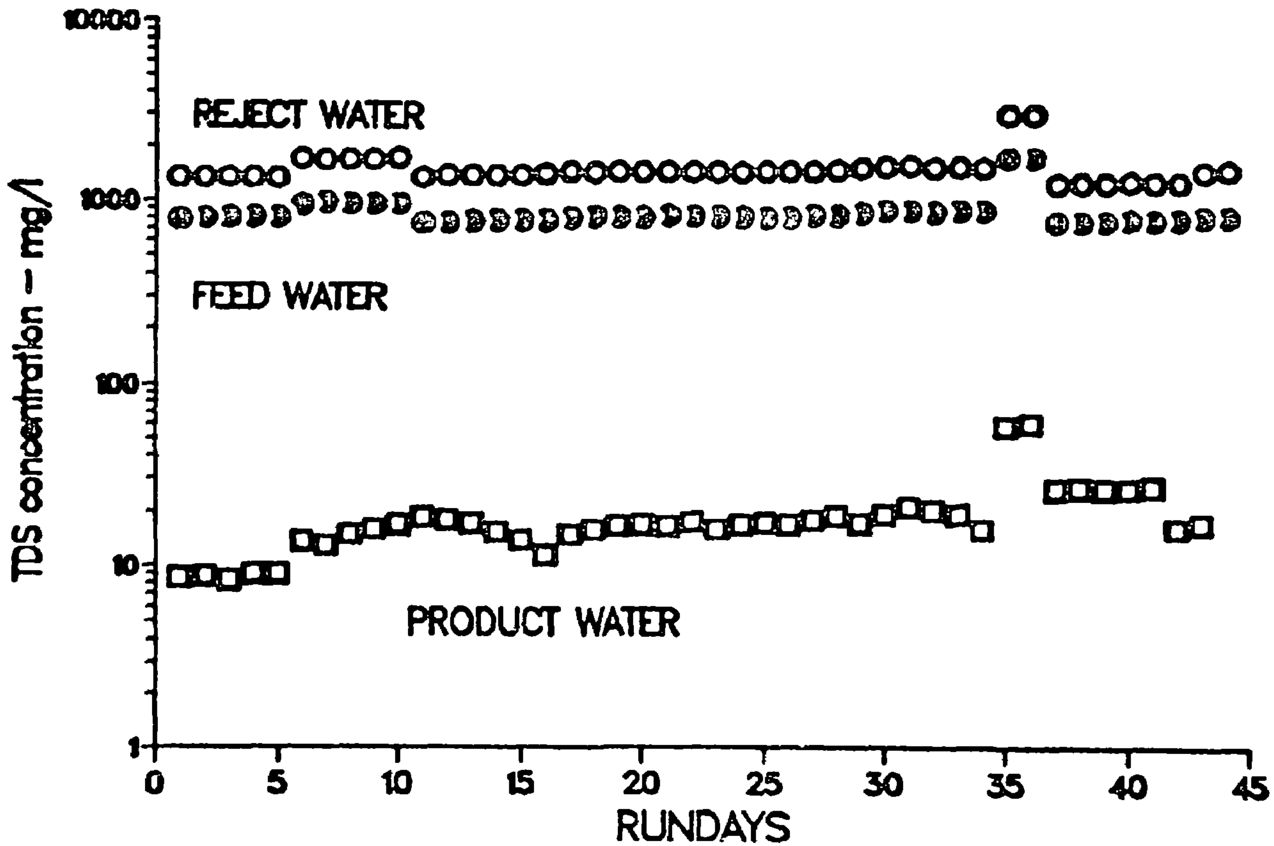

Figure 8. Removal of TDS with Dupont membrane.

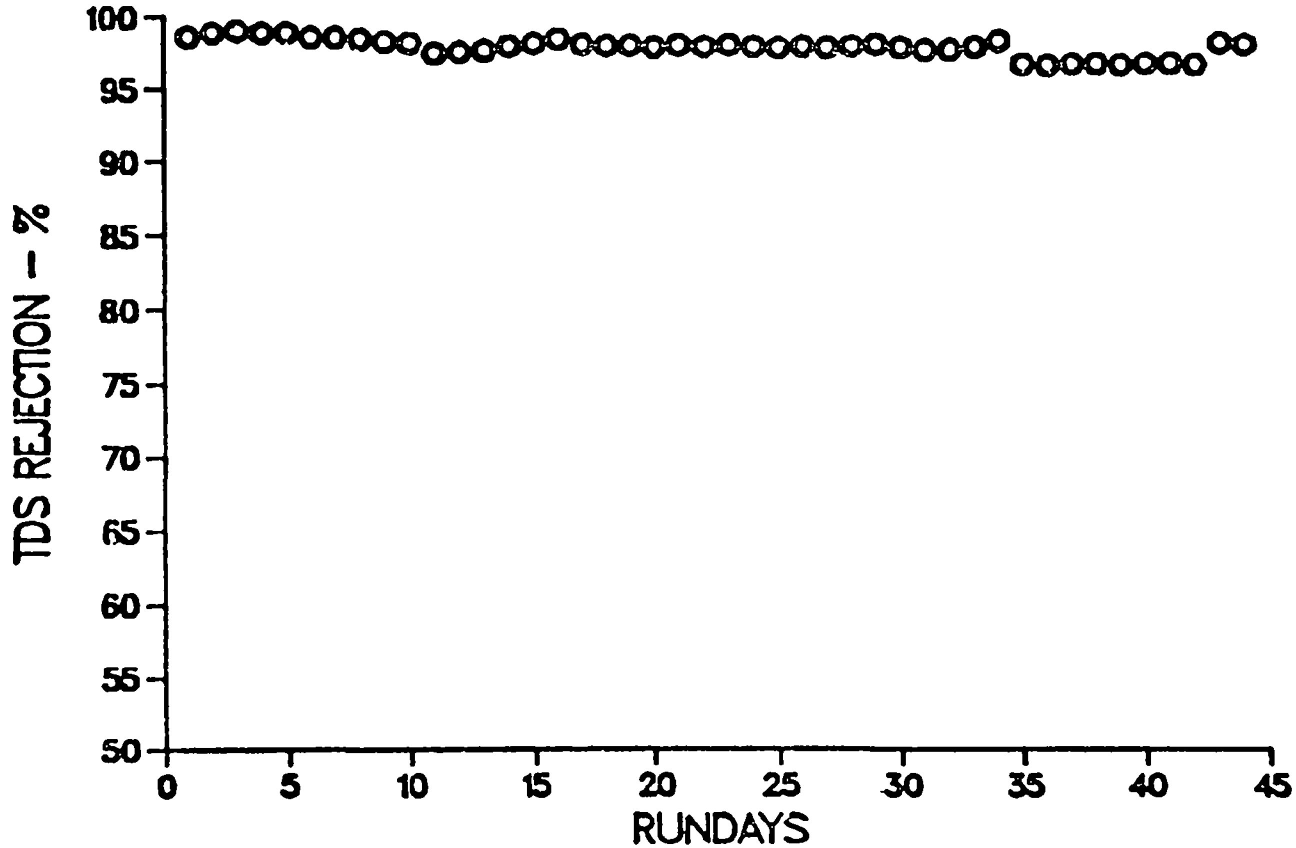

Figure 9. Rejection (percent) of TDS with Dupont membrane.

TABLE 20. SUMMARY OF CONTAMINANT REMOVAL WITH DUPONT MEMBRANE

RUN DAYS	CONTAMINANT	SAMPLES (NO.)	FEEDWATER CONCENTRATION - mg/L MIN	MAX	AVG	PERCENT REJECTION MIN	MAX	AVG
1- 5	F	12	5.2	5.4	5.3	88	96	92
6-10	Cd	14	0.66	1.79	1.22	99	99	99
	Hg	14	0.0027	0.064	0.026	65	>98	—
	Cr(+3)	14	0.15	0.39	0.26	96	99	99
11-16	As(+5)	17	0.70	1.4	1.03	98	99	99
	Se(+6)	17	1.2	2.0	1.6	98	99	99
	Cr(+6)	17	1.59	1.94	1.76	98	99	98
17-22	Pb	15	0.12	0.7	0.33	>96	>99	>98
23-28	NO_3(N)	13	12.4	13.2	12.7	93	95	94
29-34	As(+3)	16	0.38	1.05	0.61	46	84	71
	Se(+4)	16	0.37	1.75	0.88	97	99	98
34-35	Ra	2	1.83	2.19	2.01	96	97	96
36-41	U	15	0.103	0.182	0.154	96	99	98
42-43	NO_3(N)	2	13.5	13.8	13.6	95	95	95

TABLE 21. SUMMARY OF HYDRANAUTICS MEMBRANE OPERATIONAL DATA

RUN DAYS	1-3	4-6	7-9	10-13	14-16	17-20	21-23	24-25	26-27	28-29	AVG DAY 1-29
SOURCE OF WATER	B	B	B	B	B	C	B	A	B	B	1-29
CONTAMINANTS	Cd	F	As+5	Mo	Pb	U	As+3	Ra	Cu	NO_2	--
	Hg	--	Se+6	--	NO_3	--	Se+4	--	--	--	--
	Cr+3	--	Cr+6	--	--	--	--	--	--	--	--
SAMPLES/READINGS	12	12	12	15	12	12	12	6	6	4	--
FEEDWATER pH UNITS											
--AVG	5.2	5.9	5.8	5.6	5.7	7.5	5.8	6.5	5.9	6.4	6.0
--MIN	5.1	5.6	5.6	5.5	5.4	6.6	5.5	6.2	5.7	6.4	5.8
--MAX	5.2	6.2	5.9	5.7	6.6	8.3	5.2	6.7	6.1	6.5	6.3
FEEDWATER TEMP (C)											
--AVG	26	31	32	33	34	33	34	32	31	31	32
--MIN	19	27	26	26	25	27	29	26	28	23	25
--MAX	32	34	40	38	39	40	40	37	34	40	37
FEEDWATER PRESS (PSIG)											
--AVG	292	286	268	284	298	294	299	280	275	254	283
--MIN	265	275	260	260	290	265	295	260	270	250	269
--MAX	315	295	275	300	310	315	305	300	280	260	296
FEEDWATER FLOW (GPM)											
--AVG	7.1	6.8	6.6	6.3	6.3	6.1	5.9	5.9	5.5	5.1	6.2
--MIN	7.0	6.5	6.4	6.0	6.0	6.0	5.4	5.6	5.5	4.9	5.9
--MAX	7.3	7.0	6.7	7.1	6.5	6.4	5.1	6.1	5.7	5.2	6.3
RECOVERY(%)											
--AVG	10.0	11.4	10.6	10.3	11.1	10.8	11.1	10.4	11.0	10.4	10.7
--MIN	8.9	10.2	8.9	7.1	9.2	7.8	10.0	8.4	9.7	8.7	8.9
--MAX	12.2	12.8	12.5	11.6	12.0	12.6	12.6	12.6	11.9	13.2	12.4

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

TABLE 22. SUMMARY OF HYDRANAUTICS MEMBRANE TEST DATA

RUN DAYS	1-3	4-6	7-9	10-13	14-16	17-20	21-23	24-25	26-27	28-29	AVG
SOURCE OF WATER	B	B	B	B	B	C	B	A	B	B	DAYS
CONTAMINANTS	Cd	F	As+5	Mo	Pb	U	As+3	Ra	Cu	NO_2	—
	Hg	—	Se+6	—	NO_3	--	--	—	--	—	--
	Cr+3	—	Cr+6	—	—	--	--	--	--	--	--
SAMPLES/READINGS	12	12	12	15	12	12	12	6	6	4	—
FEED WATER CONC (mg/L)											
TDS-AVG	629	747	590	571	685	575	511	1579	518	517	—
TDS-MIN	620	680	570	560	590	560	500	1550	510	510	--
TDS-MAX	640	790	600	590	710	590	520	1600	520	520	—
HARDNESS-AVG	178	170	145	140	144	354	113	515	130	130	--
HARDNESS-MIN	170	160	150	140	110	350	105	510	130	130	—
HARDNESS-MAX	190	180	150	140	155	360	130	520	130	130	--
CHLORIDE-AVG	236	215	197	199	196	88	190	534	175	185	—
CHLORIDE-MIN	225	200	190	190	190	90	175	525	170	170	--
CHLORIDE-MAX	245	225	205	210	205	95	200	545	185	195	—
CALCIUM-AVG	28	28	25	24	26	95	21	85	21	19	--
CALCIUM-MIN	25	28	22	21	21	89	18	77	19	18	—
CALCIUM-MAX	29	29	27	29	33	98	22	88	22	20	--
SODIUM-AVG	90	125	79	88	126	27	88	230	95	97	—
SODIUM-MIN	83	124	69	72	104	25	74	203	94	97	--
SODIUM-MAX	98	145	84	98	141	29	94	238	97	98	—
PERCENT REMOVAL											
TDS-AVG	97	98	97	97	97	97	96	95	95	95	96
TDS-MIN	96	98	95	96	96	97	93	95	95	95	96
TDS-MAX	98	99	97	97	97	97	96	95	96	95	97
HARDNESS-AVG	99	99	99	99	99	99	98	98	98	98	99
HARDNESS-MIN	99	99	99	99	99	98	98	98	98	98	98
HARDNESS-MAX	99	99	99	99	99	99	99	98	98	98	99
CHLORIDE-AVG	96	97	96	96	96	92	94	93	93	94	95
CHLORIDE-MIN	95	96	95	95	95	91	93	92	93	93	94
CHLORIDE-MAX	97	97	97	97	97	95	96	94	94	95	96
CALCIUM-AVG	>98	>98	>98	>98	>98	98	>99	98	97	97	>98
CALCIUM-MIN	>98	>98	>98	>98	>98	98	>99	97	97	96	>98
CALCIUM-MAX	>98	>98	>98	>98	>98	98	>99	98	97	97	>98
SODIUM-AVG	99	99	98	98	98	94	95	94	95	92	96
SODIUM-MIN	99	98	98	98	96	92	94	93	95	92	96
SODIUM-MAX	99	99	98	99	98	95	96	95	95	93	97

A - CHWA Raw Water
B - CHWA Treated Water
C - FL Ground Water with Natural U

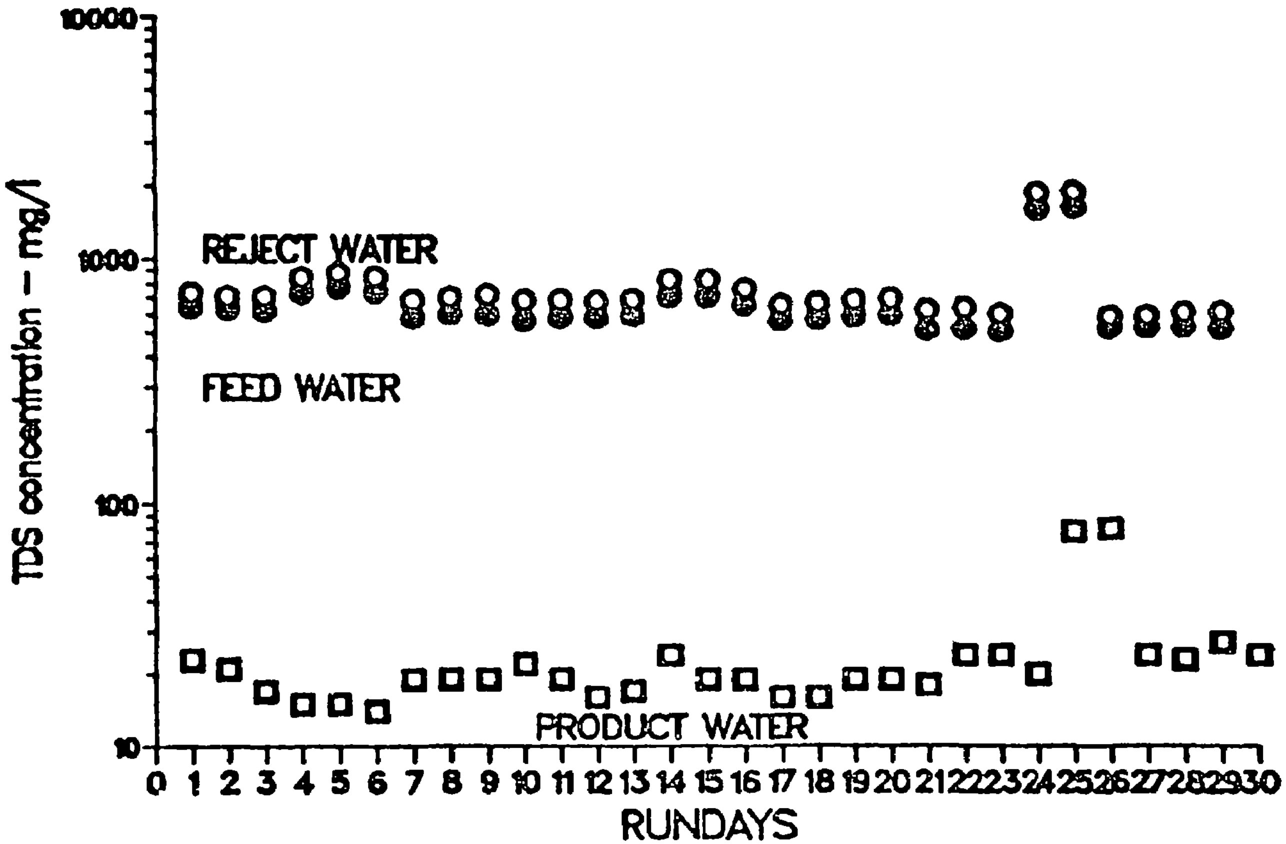

Figure 10. Removal of TDS with Hydronautics membrane.

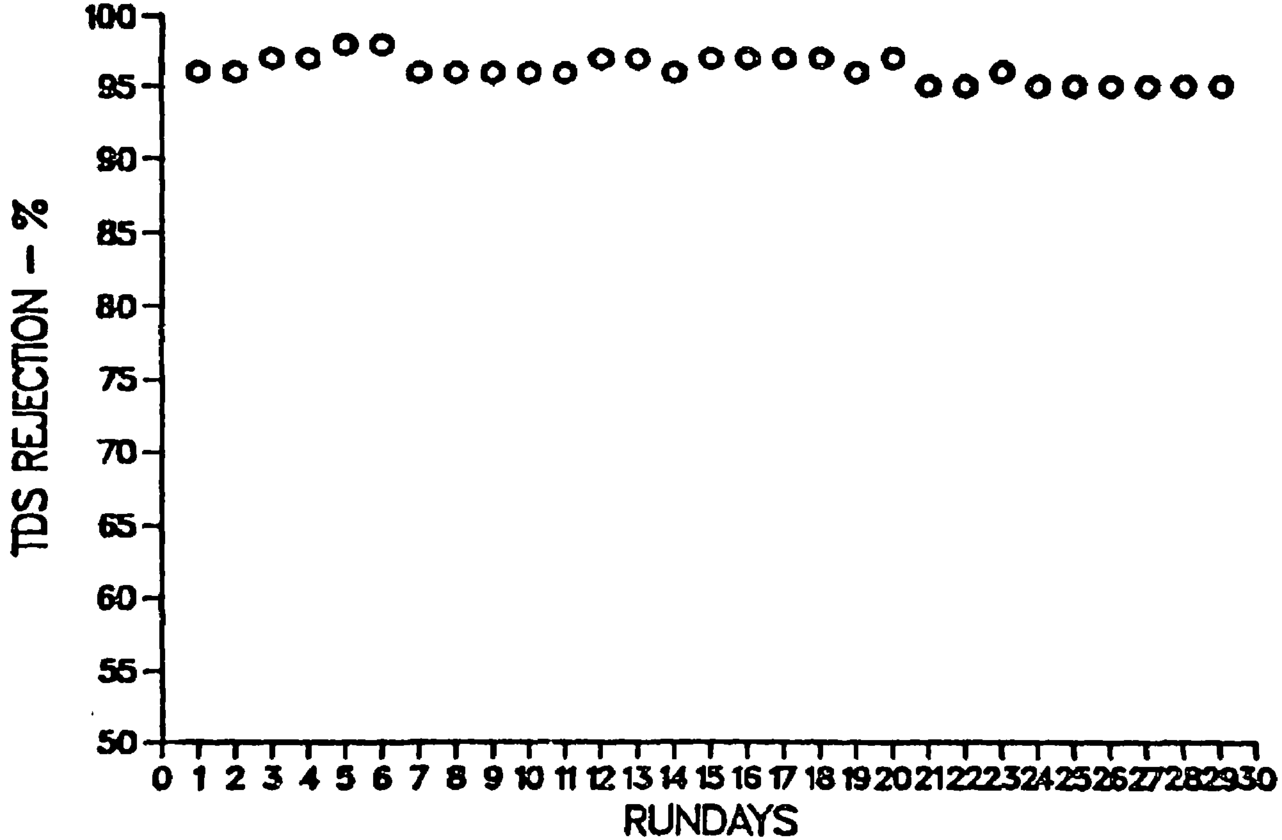

Figure 11. Rejection (percent) of TDS with Hydronautics membrane.

TABLE 23. SUMMARY OF CONTAMINANT REMOVAL WITH HYDRANAUTICS

RUN DAYS	CONTAMINANT	SAMPLES (NO.)	FEEDWATER CONCENTRATION-mg/L MIN	MAX	AVG	PERCENT REJECTION MIN	MAX	AVG
1- 3	Cd	12	1.17	1.36	1.31	99	99	99
	Hg	--	--	--	--	--	--	--
	Cr(+3)	12	0.86	1.46	1.23	99	99	99
4- 6	F	12	14.0	16.0	14.5	98	98	98
7- 9	As(+5)	12	1.3	2.0	1.7	96	99	98
	Se(+6)	12	2.0	3.2	2.7	99	99	99
	Cr(+6)	12	4.16	5.96	4.46	97	98	98
10-13	Mo	15	1.6	4.3	2.4	88	>98	>97
14-16	NO_3(N)	12	18.1	43.1	27.1	96	98	97
	Pb	12	1.7	4.8	2.6	98	99	99
17-10	U	12	0.252	0.310	0.277	99	99	99
21-23	As(+3)	11	0.8	1.1	0.92	5	75	46
	Se(+4)	12	1.0	2.4	1.5	93	98	95
24-25	Ra(pCi/L)	6	7.86	9.83	8.91	96	98	97
26-27	Cu	6	4.8	5.9	5.1	97	98	97
28-29	NO_2	4	4.8	4.8	4.8	90	92	92

SECTION 6

SUMMARY AND CONCLUSIONS

GENERAL

A small recirculating RO pilot plant system was operated with five different state-of-the-art membranes to determine the rejection values for 13 inorganic contaminants from ground water. Because of various factors, the operating test conditions were not identical for all the membrane tests. For example, operating pressures varied from a low average of 1318 kPa (190 psig) (Filmtec) to a high average of 2650 kPa (384 psig) (DuPont). Recovery varied from around 10 percent for the Filmtec, Toray and Hydranautics membranes to 50 - 60 percent for the Dow and DuPont hollow fiber membranes. Some difficulties also occurred in maintaining constant operating conditions of pressure and temperature during each individual (one-three day) test run. Consequently, comparison of the performance of the membranes is not considered totally valid. Nevertheless, the results of the study, as summarized in Table 24, show a general pattern of removals for the contaminants studied for the five membranes. Furthermore, the results can provide general guidance for estimating the approximate removals that can be achieved by reverse osmosis treatment. A short summary and general discussion for each contaminant follows.

NATURAL SUBSTANCES

Three different test waters were used each having a different background concentration of the natural substances monitored, TDS, hardness, chloride, calcium, sodium. For all five membrane tests, TDS, hardness and chloride analyses were conducted on raw, product, rejects waters. Only during the last two series of tests for the Dupont and Hydranautics membranes were the calcium and sodium tests performed in addition to TDS, hardness and chloride.

Because extensive data exists on the removal of the natural occurring substances measured, the primary reason for the monitoring of these substances was to evaluate the general performance of the membranes during the testing period.

All of the membranes averaged above 95 percent removal of TDS with some averaging 98 percent. One membrane (Filmtec) showed a noticeable decline in TDS rejection during the first 40 days of test run from around 98 percent to 85 percent. After the 40th day, TDS rejection returned to the initial level of around 97-98 percent and remained constant for the last 30 plus days. The reason for the decline is not known, but it suggested that some problem existed and thus the removal results of specific contaminants tested during this period may be lower than that achieveable under proper membrane performance.

TABLE 24. SUMMARY OF REVERSE OSMOSIS PILOT PLANT TESTS

MEMBRANE INFORMATION	DOW	DUPONT	FILMTEC	HYDRANAUTICS	TORAY
Material	CTA	ARAMID	Non-C	MCA	CA
Configuration	HF	HF	SW	SW	SW
Model No.	5K	B9 0440-0-42	SW30-4021	P/N4040	SC3100
CHEMICAL REMOVAL DATA-%					
Arsenic +3	75	71	69	46	65
Arsenic +5	98	99	99	98	99
Cadmium	98	99	99	99	98
Calcium	NA	99	NA	>98	NA
Chloride	93	94	92	95	93
Chromium +3	97	99	99	99	NA
Chromium +6	96	98	97	98	98
Copper	NA	NA	NA	97	NA
Fluoride(pH)	91(6.3)	92(6.2)	83(6.8)	98(5.9)	90(5.8)
Hardness	98	99	98	99	99
Lead	96	>98	97	97	98
Mercury (I)	14	NR	78	NA	NA
Molybdenium	NA	NA	NA	>97	NA
Nitrate	85	94	75	99	67
Nitrite	NA	NA	NA	92	NA
Radium	97	96	NA	97	NA
Selenium +4	98	98	NR	95	97
Selenium +6	99	99	98	99	99
Sodium	NA	96	NA	96	NA
TDS	96	96	95	96	95
Uranium	99	98	99	99	NA
TEST CONDITIONS					
RUN DAYS	73	43	74	29	104
AVERAGE:					
% recovery	59.0	50.0	10.4	10.7	9.8
Feed pressure	277	384	191	283	282
Influent pH	6.3	5.8	6.7	6.0	5.7
Influent temp	24	25	29	32	35
Flow rate (GPM)	6.3	4.5	4.0	6.2	6.7

NA - Not available
NR - Not reportable

All of the membranes removed above 98 percent of total hardness and 93-95 percent of the chloride. Data from the last two series of tests for the Dupont and Hydranautics membranes showed average removals of around 98 percent for calcium and 96 percent for sodium. Because calcium is the primary constitutent of total hardness, calcium removal results should be similar to hardness removal as was found. All results for the removal of the naturally occurring substances were consistent with manufacturer's guidelines for performance.

SPECIFIC CONTAMINANTS

Arsenic

Arsenic can occur in four oxidation states; however, it is normally found as an anion in only the trivalent (arsenite) and pentavalent (arsenate) forms. Each of the two oxidation states forms several species in natural waters. The soluble arsenate species are H_3AsO_3, $H_2AsO_3^{-1}$ and $HAsO_3^{-2}$ with the most predominant one (in the pH 4 - 10 range) being the neutral species H_3AsO_3. The soluble arsenite species are four: H_3AsO_4, $H_2AsO_4^{-}$, $HAsO_3^{-2}$ and AsO_3^{-3}. Of these four, the most significant ones are $H_2AsO_4^{-1}$ and $HAsO_4^{-2}$.

The arsenic removal data for all the membranes show excellent removals (greater than 98 percent) for arsenic +5 and low and variable removals (20-95 percent) for arsenic +3. The arsenic +3 removals averaged between 40-70 percent for the five membranes. The reason for the low arsenic +3 removal is assumed to be due to the neutrality of the H_3AsO_3 arsenite species. The general rule of thumb is that rejection is directly proportional to the ionic charge; the higher the charge the better the removal by RO.

Arsenic +3 can be oxidized to arsenic +5 rather easily. The assumption is made, therefore, that the variability of removal may be caused by some of the arsenite being oxidized to arsenate during the test runs resulting in higher removal. The arsenic analyses were performed for total arsenic only and no attempt was made to determine if the arsenite remained as arsenite throughout the entire test runs.

Cadmium

Cadmium is a divalent cation and very high removals by all RO membranes were anticipated. The test data confirmed the expected results; the average percent removal for all membranes was over 98 percent.

Chromium

Chromium is similar to arsenic and selenium in that it has several oxidation states. In aqueous systems, the most significant valences are the trivalent (chromium +3) and the hexavalent (chromium +6) forms. Trivalent chromium occurs as a cation Cr^{+3} and hexavalent chromium as an anion 45 as either chromate ($HCrO_4^{-}/CrO_4^{-2}$) or dichromate ($Cr_2O_7^{-2}$). Both anion forms are very soluble in water and the formation of each is pH dependent. The chromate ion exists in alkaline water and the dichromate ion in acidic water.

The test data showed excellent removals for both chromium +3 and chromium +6. All membranes achieved better than 96 percent removal of both forms and several membranes averaged 99 percent removal of chromium +3. Therefore, chromium is easily removed by RO regardless of the form found in the water source.

Copper

A copper test was added to the last study with the Hydranautics membrane because EPA has proposed that it, along with several other new inorganic contaminant, be considered for regulation (9). To provide some data, a two day (6 samples) test was conducted with the Hydranautics membrane. Copper being a divalent cation similar to cadmium, lead, and calcium, good removals were expected. The short test period proved this to be true with the average removal being 97 percent. The conclusion is, therefore, that if copper is found in the source water it should be easily removed from drinking water by reverse osmosis.

Fluoride

The Dupont Engineering Design manual states that removal of fluoride and bicarbonate for their B-10 permeators are pH dependent. Their data show about 50% removal at pH 5.5 increasing to about 95 percent removal at about pH 7.5. The test data for the five membranes showed a range of removal average from 83 to 98 percent. The tests program was not designed to evaluate the effect of pH, but because the feed water pH did occasionally vary, some variation in pH did happen. Unfortunately, pressure and temperature also varied making it difficult to determine the effect of pH alone. A review of the fluoride data obtained showed only the Dow membrane data having a wide range of pH values (4-7) for feed water and these data do indicate a trend of increasing removals with increasing pH (Figure 12).

Lead

Lead is a divalent cation and forms various carbonate and hydroxide complexes in natural waters. The test data for the five membranes showed high removals of above 96 percent removal for all membanes with two of them averaging 98 percent. The data thus indicated that lead is easily removed from ground water by reverse osmosis.

Mercury

Mercury has three basic oxidation states in aqueous solutions: (1) the pure metal, Hg; (2) the monovalent ion (mercurous), H^{+}; and (3) the divalent ion (mercuric), Hg^{+2}. Besides forming the common inorganic salts, mercury has the capacity to form organic complexes, the most significant being the very toxic methylmercury ion, CH_3Hg^{+}. In water having a pH above 5, the most

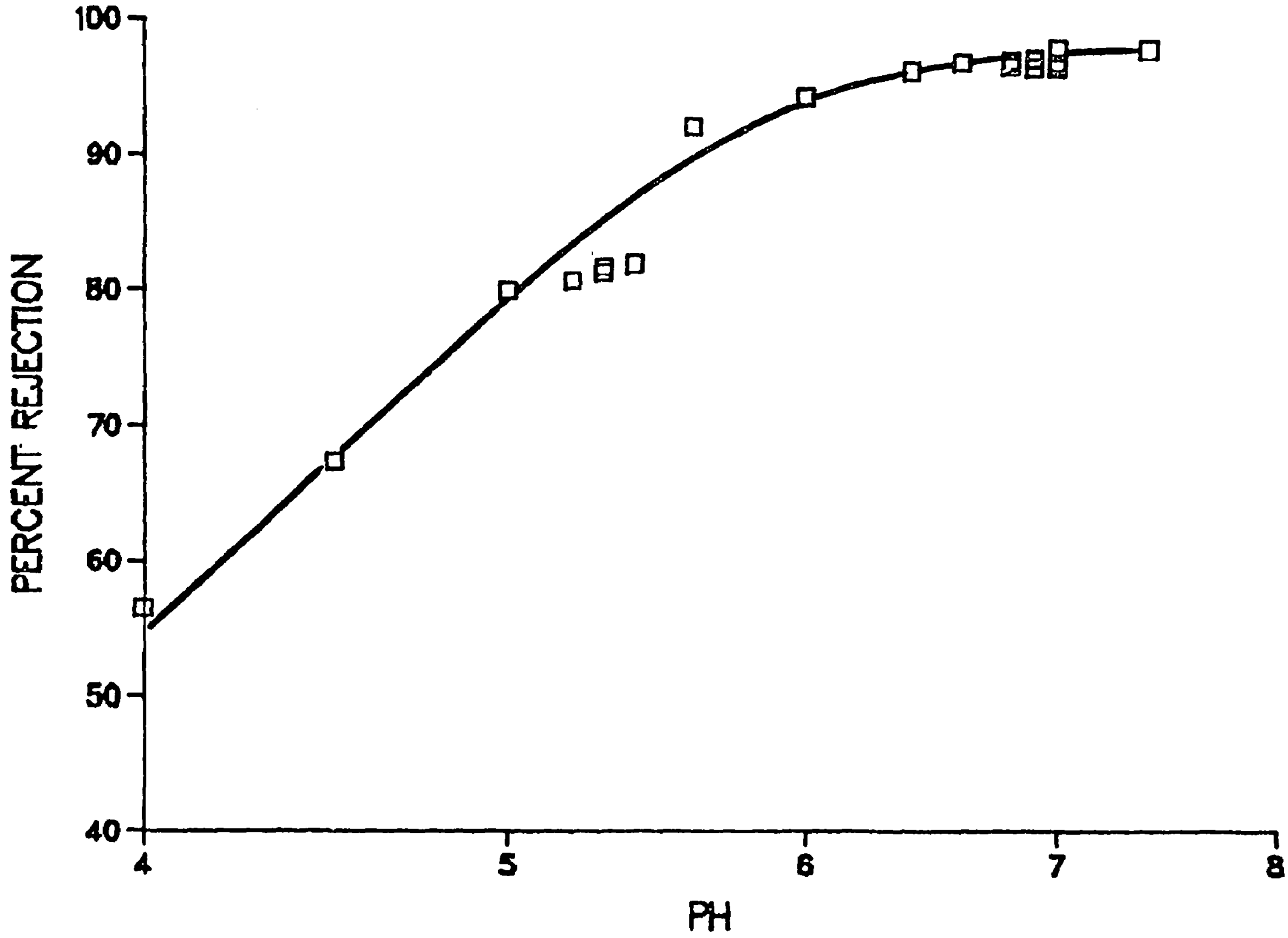

Figure 12. Effect of pH on Fluoride Removal

predominant mercury species is metallic mercury, Hg^0 with a relatively low solubility. In high chloride concentration waters, the solubility of mercury increases with the formation of the uncharged complexes of $HgCl_2$ and $Hg(OH)_2$. Tests were not designed to evaluate the effect of pH, but because the pH of the feed water varied to some degree some variation in pH did occur. Unfortunately, pressure and temperature also varied making it difficult to determine the effect of pH alone.

Another important characteristic of mercury is the tendency of mercury to adsorb to various materials. In the initial RO studies when a prefilter was in line, a decrease in the total mercury content of the water was observed. After the filter was removed, this decrease was not as great, thereby suggesting that some of the mercury was adsorbing to the filter.

Because of various reasons, data on mercury removal were reported for only three membranes and this data varied from a low average of 14 percent to a high of 80 percent. It is difficult to determine the cause of the variability, but based upon the results of other contaminants it is unlikely to be membrane differences.

Molybdenum

A molybdenum test run was added to the study during the last series of tests with the Hydranautics membrane because molydbenum appeared on the EPA inorganic list of possible or proposed regulations (9).

Molybdenum is a transition metal that can exist in oxidation states from 2^- to 6^+. In aqueous solution, molybdenum will occur in various forms depending on the water composition and the oxidation-reduction potential of the water. In most natural waters, the most predominant species is MoO_4^{-2}.

Although the test data is limited to one membrane, the result of 97 percent removal suggests that molydbenum is easily removed by RO treatment.

Nitrate

Nitrate (NO_3^-) is a common ground water contaminant and RO information indicates that it is not highly rejected by most membranes. The test data for the five membranes showed removal averages from 67 to 99 percent.

Unfortunately, the lack of very tight operating conditions prevents making any firm conclusion regarding specific membrane rejection capability. The general conclusion is that nitrate is not as highly rejected as most contaminants with rejections in the 65-90 percent range.

The general literature suggests that some of the newer RO membanes may have a greater capability to remove nitrate than the older membrane type. Again, because of the lack of very tightly controlled conditions, it is difficult to draw any firm conclusion from this study.

Nitrite

Because nitrite (NO_2^-) is proposed for consideration as an EPA regulated contaminant, a nitrite test was added to the last study with the Hydranautics membrane. The very limited test results (2 days, 4 samples) indicated good removal. The two day test results showed a 90-92 percent removal range with an average removal of 92 percent. The nitrite average of 92 percent was slightly less than the removal average of 97 percent for nitrate for this membrane. The operating pressures differed by 1960 kPa (284 psig) (average) for the nitrate test to 1750 kPa (254) psig (average) for the nitrite study. Whether this pressure difference is the reason for the difference in removal is not known.

Radium

Radium is a divalent cation that has chemical and physical properties similar to the elements in the alkaline earth metals group - calcium, magnesium, barium and strontium. Because of radium's similarity to calcium and magnesium (hardness elements), removal of radium by RO should be similar to the removal of these two elements and, of course, total hardness.

Data exist on the removal of radium from ground water by full scale RO systems (10). For this reason and also because of the complexity of radium analyses, only one day tests were completed on each membrane. The test data confirm the full scale system results. All systems removed around 96-97 percent of the naturally occurring radium in the ground water. Furthermore, these results were very similar to the removal values reported for hardness and calcium. Thus, RO is considered a good method for radium removal.

Selenium

Selenium is somewhat similar to arsenic in that selenium has several oxidation states, but only two are predominant in water: selenium +4 and selenium +6. Moreover, like arsenic, selenium occurs as an anion in water and thus has acid characteristics.

Selenium +4 forms two primary species in water, $HSeO_3^-$ and SeO_3^{-2}. At pH 7, the predominant one is the divalent SeO_3^{-2}. Selenium +6 forms only one species, in water, the divalent SeO_4^{-2}.

The RO test data showed high removals (95-99 percent) for both selenium +4 and selenium +6 by all membranes. Consequently, removals are not valence dependent: both forms are easily removed by RO and the valence is not important.

Uranium

Uranium occurs as an anion complexer in natural water and the species that predominate in the pH range of 7-10 are likely to be the carbonates forms, $UO_2(CO_3)_2^{-2}$ and $UO_2(CO_3)_3^{-4}$. Because of the high ionic charge, high